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MATERIAL AND MECHANICAL CHARACTERIZATIONS FOR BRAIDED COMPOSITE PRESSURE VESSELS

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ABSTRACT

An investigation into the material and mechanical characterizations of braided composites for pressure vessel design is conducted. The materials include S-2 Glass, Carbon, and Aramid (Kevlar) fiber reinforced epoxy composites (glass/epoxy, carbon/epoxy, and Kevlar/epoxy, respectively). Twelve material configurations are evaluated. Width-effects determination is conducted to examine the effect of cutting braided specimens from larger panels. Tensile strength and tensile modulus are measured on each material at room temperature and humidity, and on materials conditioned via exposure to a 560°F environment for one second but tested at room temperature and humidity. Resistance to slow and fast heat application (slow and fast cook-off, respectively) is examined to qualitatively determine material response. Additionally, a literature review of hygrothermomechanical effects is conducted.

Width effects determination testing shows that as specimen width is increased, average tensile strength increases sharply and levels off to a relatively constant value above a specimen width of 2 inches. Thus, the specimen width is set at 2 inches in the tensile test portion of the research.

Mechanical property data are presented for the various material configurations. Braid angle is shown to have a strong influence on tensile properties in single-ply braided composites. Single-ply and dual-ply S-2 glass/epoxy composites have higher tensile strength and tensile modulus than their Kevlar/epoxy counterparts of similar configuration. Combining Kevlar/epoxy and carbon/epoxy materials into a composite sandwich significantly improves the tensile properties of Kevlar/epoxy single-ply and dual-ply materials.

Material properties are examined with respect to resistance to heat application. All specimens subjected to slow cook-off testing for one hour at 237.50°F, 356.25°F or 475.00°F show visible signs of discoloration. Fast cook-off testing investigates a material's response to intense heat. Fast cook-off testing, using an oxyacetylene torch, lasted for fifteen minutes or until structural integrity was lost. Only one configuration, a Kevlar/epoxy-carbon/epoxy-Kevlar/epoxy-steel foil sandwich retained structural integrity for the full fifteen minutes. Single-ply materials, and especially Kevlar/epoxy materials, demonstrate the least resistance to intense heat.

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1 INTRODUCTION

Composite materials employing fiber reinforcement of a resin matrix are becoming more common as candidates for improving the qualities of mechanical structures. The single greatest advantage of using fiber reinforced composites (fiber/matrix materials) from a design standpoint is the ability to match material characteristics with structural function. Given a known function, composite materials can be fabricated to optimize the positive qualities of a structure. The designer, armed with this foresight, is no longer constrained by fixed material properties. Variations of fiber types, fiber lay-up, stacking sequence, matrix material and structural geometry provide a nearly infinite array of material properties.

The combinatorial nature of composite structural design can become overwhelming. This is especially true for structures that must be efficiently engineered for weight, cost, strength, or any other limiting attribute, whether considered alone or in any combination. It is relatively easy to design too conservatively with any material. The challenge posed to designers using advanced materials, such as fiber/matrix composites, is to optimize a multidimensional design method.

The lack of a standard, universally accepted method for incorporating advanced composites in design leads to the method of test and evaluation. Candidate materials for a structural design are chosen based on previous operational observations or because the fiber/matrix combination exhibits (or is likely to exhibit) traits that are deemed desirable in the final structure.

The use of composite materials in the marine, aerospace, and related fields has been of increasing interest to designers and operators in those areas. Weight, strength, and robustness are measures of effectiveness that are usually the driving factors in

optimizing final products. Advanced composite advantages include relatively high strength-to-weight ratios, high resistance to corrosive attack, ease of production, and low-maintenance.

One area of interest expressed by designers and operators is in composite pressure vessels. Because of their cylindrical shape, filament winding of composite pressure vessels is common [1 - 4]. Braided composites are increasingly becoming candidate materials for several reasons. A few of these reasons are as follows:

1. Braids have strength and elastic properties approximating those of corresponding angle-plied laminates with greatly enhanced impact damage resistance [5].

2. Braided structures do not have to rely on interlaminar shear strength of the matrix to prevent certain failure modes as in angle-plied laminates [6].

3. Hybrid yarn braids are easily manufactured by using different yarns on different spools [6].

4. Unsupported braids up to eight inches in diameter are possible, and with mandrel overbraiding, six foot diameters are achievable [7].

5. Complex shapes such as bends, cross-sectional area changes, and tapers can be braided with relative ease [8].

Braided materials consist of fibers intertwined with each other in a specified sequence. In order to be consistent with the literature researched for this project, braided composites are defined by their dimensional characteristics. A two-dimensional braid is constructed with two intertwined fiber bundles. The introduction of a third, unidirectional fiber or fiber bundle results in a triaxially braided

material; however, the braid is still categorized as two-dimensional. A three-dimensional braid is constructed with three or more fiber bundles intertwined into the structure. In three-dimensional braids, a percentage of fibers is woven into the fabric in the orthogonal direction, resulting in improved through-thickness properties unattainable by single-ply composite laminates.

The over/under operation within a single braided layer produces symmetry that is only achievable using two layers of traditional unidirectional composite laminae. Braid angle, denoted by θ, is the acute angle formed by the off-axis (wrap (bias) direction) fibers with the longitudinal axis (braid direction). See Fig. 1. Braid angles are typically in the range of 10^0 to 85^0. Radial hoop strength of cylindrical structures is improved by increasing the braid angle. Likewise, longitudinal stiffness is enhanced by decreasing the braid angle [7]. Axial strength can be improved further by introducing triaxial braiding where the third fiber is incorporated in the 0^0 direction.

The purpose of this research is to examine a variety of fiber reinforced polymeric composite materials proposed for use in an overbraided composite pressure vessel. The applications of such a design include self-contained breathing tanks for use by underwater divers or fire fighters, submersibles, and rocket motor cases.

Material and mechanical characterizations are important in examining candidate materials. Material properties of interest are primarily heat-related. Resistance of material specimens to both slowly increasing temperatures and intense, rapidly rising temperatures indicates performance aspects in abnormal environments. Mechanical characterizations include tensile strength and tensile modulus measurements for specimens maintained and tested at room temperature and humidity, and samples environmentally conditioned at a higher temperature but tested at room

temperature and humidity. The effect of test specimen width on the reported results is also important to ensure that the tests reliably predict mechanical properties of the fabricated structures.

The proposed pressure vessel could potentially be exposed to environmental effects as well as structural loads. The potential for environmental impact on a structural design can be significant. A major survey and review of temperature and moisture effects are undertaken to aid in the assessment of proposed materials to withstand their intended environment. These hygrothermomechanical effects are documented for various composite configurations.

2 LITERATURE REVIEW

2.1 Braided Composites: Mechanical Characterizations

According to Croon [9], the mechanical characteristics of braided materials are strongly dependent on their geometry. Given the large number of possible geometries of braided materials and the numbers of materials which can be braided, a restricted set of materials is chosen for examination. The materials which will be considered are carbon, glass, and Kevlar fibers in polymeric matrices. The only types of braiding considered are those which are two-dimensional or thin three-dimensional where the depth dimension is much smaller than the length and width dimensions.

There is the potential for braided materials to exhibit increased through-thickness strength and impact damage tolerance without a major negative effect on tensile properties. Ko [10] conducted experiments comparing tensile strengths and moduli of three-dimensional braided carbon/epoxy composites to their corresponding laminates. He found that, as expected, the tensile strengths and moduli of three-dimensional braided composites were lower than those of unidirectional laminates. However, the three-dimensional braided composites showed far superior tensile strength and modulus properties compared with angle-ply laminates.

The findings that three-dimensional braided composites display improved tensile properties over angle-plied composite laminates were echoed by Simonds, Stinchcomb, and Jones [14]. They also concluded from their experiments that three-dimensional braided composite materials offered benefits in improved damage tolerance compared with laminated composites.

Gause and Alper [5] concluded that three-dimensional braided composite elastic properties were merely similar to crossplied laminates having comparable fiber angles. Their findings contradict Ko [10] and Simonds, Stinchcomb, and Jones [14].

The findings of Gause and Alper [5] led to the conclusion that by using laminate analysis, good approximations to braided in-plane elastic properties can be expected. Comparisons of their experimental and analytical results support this statement. In their research, the basic three-dimensional braid pattern (similar to three-part braided hair and denoted by [1 x 1 x 1]) is modelled as $[\pm\theta]_s$ and [1 x 1] 1/2 fixed (in which half of the yarns are held straight and the remainder are braided about the fixed yarns) is modelled as containing 50 percent 0^0 plies, as in $[\pm\theta/0_2]_s$.

Crane and Camponeschi [12] examined through-thickness fiber reinforced braided materials, generically termed multidimensional braiding. Their objectives were to investigate the effect of edge condition and braid pattern. Three types of braids were examined. The findings revealed that the tensile strength of braided materials cut to one inch widths was approximately 35 percent of that for uncut specimens woven to the one inch specimen width. Tensile moduli of cut-edge specimens were 55 percent of those for uncut specimens. Of all specimens with cut-edges that were tested, the material configured as [1 x 1] 1/2 fixed displayed the best retention of tensile properties.

In general, the results indicated that the tensile properties exhibited by braided composites appeared to be no worse than comparable angle-ply composite laminates. Important factors in deciding if braids represent a truly advantageous product include

geometric considerations (for example, what type of loads are likely to be incurred by the finished product) and fabrication considerations such as cut-edge requirements.

Mechanical properties other than tensile strength and modulus also improve with braiding. One of the primary reasons two-dimensional, triaxially braided structures have been developed is to overcome the bidirectional orthogonal primary loading limitation exhibited in woven fabrics [11].

The mechanical properties of two-dimensional triaxially braided graphite/epoxy cylinders in tension and compression were examined by Tsiang, Brookstein, and Dent [15]. They stated that yarn overlacing, as found in triaxially braided structures, may enhance the interlaminar shear strength. This is a potential advantage over ordinary angle-ply laminae, especially in laminates requiring a high degree of flexural strength as well as tensile strength.

Two-dimensional triaxially braided composites are not without drawbacks. Elastic properties of the structure may be adversely affected by highly crimped yarns brought about by the braiding process [15]. Lugar [11] expanded this to say that not only can fiber crimp be a potential problem, but braids characteristically contain a large interior void volume as well. This increased void volume may have a decidedly deleterious effect on mechanical properties of the composite.

2.2 Hygrothermomechanical Effects on Mechanical Properties

Advanced composite materials may be subjected to a variety of environmental conditions. Practical designs must be somewhat impervious to variations in operating climate and storage conditions. Ideal temperatures and relative humidity values are rarely realized outside the laboratory.

A review of the effects of temperature and moisture on mechanical properties is undertaken to understand the hygrothermomechanical effects on composite materials. In order to bound the review, only references discussing carbon, glass, and Kevlar materials are reviewed.

Komorowski [16] reviewed 328 sources of information on hygrothermal effects in continuous fiber reinforced composites. He found that tests in tension, compression, torsion, shear and flexure were used to determine mechanical properties. Properties most often reported in the literature were strength, modulus, notch-damage and impact-damage sensitivity. The properties of interest for this study are tensile strength and tensile modulus. Other properties are introduced to aid in the understanding of temperature and moisture effects as required.

The method of approach for this section of the literature review is to briefly mention broad environmental effects on resins, and then examine hygrothermal effects on carbon, glass, and Kevlar fibers and the composites they reinforce. Emphasis is maintained on composite laminates.

A good discussion on the effects of water absorption into epoxy resins was conducted by Wright [17]. His research provided many valuable points:

1. Water absorption (as measured by percent weight change after 180 hours immersion in boiling water) differed by up to a factor of ten between different resin types.
2. In nearly every case, drying and subsequent reimmersion of specimens resulted in an additional 10 percent increase in amount of water absorbed.

3. Water absorption was a positive function of humidity and temperature.

4. Water absorption caused resins to swell.

5. Moisture acted as a plasticizing agent in the resin, and hence, lowered the glass transition temperature (T_g).

6. Coatings can noticeably reduce moisture content in laminae, even if the coating is itself permeable to water.

Most temperature and moisture conditions induced degradations related to matrix-dominated properties. This point is well documented in literature concerning carbon and glass reinforced epoxy composites [18 - 22].

Daniel, Yaniv, and Peimanidis [18] tested a set of unidirectional carbon/epoxy specimens at different temperatures, moisture contents, and strain rates. They found that all longitudinal properties remain unchanged, with the exception of longitudinal modulus, which increased slightly with increased strain rate. These findings are expected since longitudinal properties are fiber-dominated. All matrix-dominated properties (for example, transverse tensile and shear strength) showed degradation with increasing temperature and moisture for a given strain rate.

The finding that the carbon/epoxy properties most affected by temperature and moisture are matrix-dominated is in concordance with the studies of Hahn [19]. He concluded that damage mechanisms present in hot and wet states include matrix plasticization, debonding between fiber and matrix, microcracking, and microvoid formation.

Lifshitz [20] also agreed with the premise that hygrothermal conditions effect matrix-dominated properties. He stated that matrix-controlled mechanical properties of carbon/epoxy laminates may be significantly altered by differences in temperature, humidity and strain rate. Conversely, his data showed that for fiber-dominated longitudinal properties on $[0^0]_8$ specimens, tensile modulus was not affected by the same conditions. Axial tensile strength, interestingly, increased with a corresponding increase in temperature and moisture content. This was thought to be due to the brittle nature of the matrix at lower temperatures. Hence, the matrix was more sensitive to stress concentrations in the regions near broken fibers. This condition diminished at higher temperatures as the matrix became more ductile.

Thermal aging of carbon/epoxy composites was conducted by Kerr and Haskins [21]. Specimens were aged at elevated temperatures of 250^{0}F and 350^{0}F for times of 100 to 50,000 hours (5.7 years). Tensile tests were conducted on the conditioned samples. Reduction in strength was significant at higher temperatures and longer aging periods. They concluded that the primary cause of mechanical property loss during thermal aging was matrix degradation. To a lesser extent, fiber degradation played a role in reducing tensile properties.

Carbon fibers are not susceptible to water absorption and thus, they do not radically change properties in a moist environment. This explains why temperature and moisture affect matrix-dominated properties more than fiber-dominated properties in carbon/epoxy composites.

Glass fibers are also impermeable to water absorption. However, thermoset glass reinforced plastics are still prone to degradation in wet conditions. Weather exposure tests showed that, in general, mechanical properties of glass/epoxy composites decreased 20 to 30 percent after 60 days of water saturated conditions [23].

Zhou [23] found that, based on the research of glass/epoxy materials water saturated longer than twenty years, there were three distinct stages of mechanical property change in the composites:

1. The early stage was characterized by quick degradation of mechanical properties. These properties gradually became constant as the specimen became water saturated.
2. The middle stage was reached when the composite settled to its wet strength. The mechanical properties of the specimen remained constant at least twenty years in this condition.
3. The last water-saturated stage was reached as structural integrity of the specimen was lost and failure of the specimen occurred.

The wet strength phenomenon observed in glass/epoxy was also documented for carbon/epoxy systems [24]. It was found that the moisture content reached a steady state and varied only slightly thereafter. In the case of a composite 0.5 inches thick, this steady-state condition was reached in ten years.

Wet specimens that have been desorbed will recover a percentage of their pre-wet strength [25, 16, 22, 23]. The amount of recovery is dependent on the wetting conditions and drying time.

Fukuda [22] found that flexural modulus recovered with drying, after being water saturated for up to 90 days at 176^0F, for carbon/epoxy, glass/epoxy, and carbon/glass/epoxy hybrids. Flexural strength and interlaminar shear strength recovery was small. Zhou [23], on the other hand, found that glass/epoxy recovered 96 percent of its original flexural strength after being water saturated for seven years.

It is interesting to note that Fukuda [22] found that the moisture contents of glass/epoxy and carbon/glass/epoxy hybrids reached a maximum and then decreased gradually. The mechanism for this decrease was not stated. He pointed out that Kasturiarachchi and Pritchard [26] also reported a moisture content reduction for water saturated glass/epoxy.

The introduction of Kevlar as a reinforcing fiber in a polymeric matrix adds a new factor to hygrothermal effects on mechanical properties. Kevlar is an organic fiber, and as such, it is prone to water absorption on its own accord. Therefore, degradation mechanisms are manifested through moisture absorption of both the matrix and the Kevlar fiber [27]. Water absorption may result in moisture-induced physical and chemical changes in Kevlar 49 fibers [28]. Because of the hygroscopic nature of Kevlar, fiber absorption must be considered in studying environmental effects [29].

Sampathkumar and Schwartz [30] examined the effects of water immersion on loosely-braided bare Kevlar fibers. Tensile tests on specimens immersed for 30 days at 70^0F revealed that the only fibers showing strength reduction were those immersed in salt water and tested dry. Samples tested in distilled water showed no strength degradation when tested dry or wet. The salt water samples tested wet also showed no reduction in tensile strength. Limited reversibility of property degradation was observed; when dried braids were subsequently reimmersed and tested wet, they displayed results comparable to other samples tested wet.

The results given in [30] should be used cautiously. As the authors pointed out, these results were for loosely-braided small-diameter Kevlar fibers. Extrapolation of data to larger structures may prove to be inaccurate. They concluded that

the attack of salt crystals on the Kevlar fibers probably represented a worst-case scenario, since the fibers were completely exposed to the harsh environment and not protected by a matrix or other fibers.

Gopalan, Somashekan, and Dattaguru [27] showed in their experiments that Kevlar/epoxy ultimate tensile strength degraded 12 percent and Young's modulus was reduced 32.5 percent after immersion in water at 158^{0}F for 20 days. Graphite/Kevlar/epoxy hybrid showed slightly less, yet significant degradations of the same properties. They concluded from their findings that fiber absorption in the case of Kevlar played a significant role in property degradation.

The flexural response of Kevlar/epoxy laminates was studied by Allred [25]. He found that strength reduction was significant for specimens at 302^{0}F and near moisture saturation. Flexural strength actually increased when measured at -67^{0}F. Khan [31] found reductions in flexural strength of Kevlar/epoxy at temperatures in the range of 77^{0}F to 203^{0}F.

Extreme environmental conditions similar to those found in the tests described above may be rarely seen by composite structures in service. The effects of service environment aging was one of the topics of investigation of Morgan, *et. al.* [32]. They found that under ambient aging conditions, ultraviolet exposure produced fiber strength degradation. (Ambient conditions were not explicitly defined in [32]. Beckwith and Wallace [33] defined ambient conditions as 40^{0}F to 100^{0}F and less than 75 percent relative humidity.) The data showed that stress exposure produced larger degradations. Most interesting, however, was the fact that the burst pressure of a Kevlar/epoxy vessel actually increased with aging. This was due to moisture sorption resulting in increased resin flexibility. (Recall Lifshitz [20].) The results do not guarantee similar results in more extreme environments for long periods of

time. However, the authors felt that in typical service environments, hydrolytically-induced fiber degradation and ultraviolet-induced fiber aging were not a serious concern.

In another study, significant performance deterioration was attributed to residual stresses caused by the expansional mismatch between fiber and matrix [34]. The stresses increased as service temperatures further deviated from composite fabrication temperature. Structural geometry may be of little help in solving this problem. In carbon/epoxy composites the linear expansivity is only a weak function of shape [35].

It is obvious after conducting this research that work presented in the literature is very limited in the area of braided fiber reinforced composite materials. In most cases, the data were presented for tests on specific material configurations of interest. As Lifshitz [20] pointed out, results can often be too specific to be valuable in the design of other structures.

2.3 Predictions of Hygrothermal Behavior of Braided Composites

Predictions of the mechanical response of braided composites have not enjoyed the same plethora of attention given to other laminated composites. Ko [36] asserted that, in general, "the properties of braided composites are not as well characterized as those for unidirectional tape or woven ply laid-up laminated composites." The myriad of braiding options has resulted in large areas of unknown mechanical properties.

The attention being focused on attempts to optimize braided composite characteristics has caused a lack of development in understanding temperature and

moisture effects. The introduction of braided composites to greater structural use should begin to reverse this trend. As the demand for braids increases, more information regarding environmental performance characteristics will be required.

In the absence of substantial amounts of specific data for braided composite hygrothermomechanical behavior, broad conclusions developed from other studies may provide some insightful information. The confirmation of these hypothetical deductions must be conducted through controlled tests. Mechanics of moisture absorption and causes of failure due to wet and hot environments are examined. Predictions for the performance of Kevlar/epoxy braided composites are attempted.

Moisture absorption in composites has been analyzed and found to be a function of matrix properties [17, 33], specimen construction [17, 22, 27, 29, 32], and environmental conditions [17, 25, 27, 32, 34]. Different combinations of properties, constructions, and conditions produced various degrees of hydrolytic states.

Matrix properties are controllable from the outset of specimen construction by the designer and fabricator. It is axiomatic to state that not all epoxy systems behave the same, and that no single resin may contain all the desired properties in a composite structure. However, it is prudent that some attention be paid to the matrix hygrothermal properties when operation in a hot or moist environment is expected.

Braided composite structures are not exempt from moisture absorption through the matrix. Therefore, they are equally susceptible to degradation of the resin physical properties, such as swelling and reduction in glass transition temperature, as are comparable angle-plied composite laminates.

Specimen construction is important from the viewpoint of fiber orientation and processing methods. Gopalan, Somashekar, and Dattaguru [27] compared the

degradation in strength and stiffness of unidirectional, bidirectional, and randomly-oriented E-glass reinforced composites after hygrothermal conditioning. Unidirectional orientation displayed the best strength retention, and randomly-oriented fibers showed the most severe degradation.

Although it was not specifically mentioned in [27], the reduction of strength in randomly-oriented fiber composites may be a strong function of the void content. The necessarily high number of fiber cross-overs creates the opportunity of "dry" fiber contact. The lack of resin in such areas could produce "water pockets" that trap and hold moisture. Braided composites are at a greater risk to this void problem than angle-plied composite laminates. (Recall Lugar [11].) The large interior void volume of braided composites may continue to be a problem until improved specimen fabrication is developed.

Environmental conditions also affect the moisture response of composites and their resin systems. At higher temperatures, water absorption is accelerated due to the expansion of voids and microgaps at the fiber-matrix interface. Swelling of the composite also takes place allowing even more moisture to be absorbed [27]. Wright [17] pointed out the relationship between moisture absorption in resins and relative humidity and temperature. As relative humidity increased, equilibrium moisture content rose. Likewise, an increase in diffusion coefficient was witnessed for higher temperatures.

Braided composites may be equally prone to moisture degradation due to environmental conditions as other composite configurations. The unique properties of braids do not prohibit these types of moisture responses. There is equally little evidence that braids may be worse than angle-plied composite laminates for the same conditions.

The failure mechanisms of hygrothermally conditioned composites has been discussed by several authors [37, 17, 20, 25, 27, 28, 29]. Most research concluded that accelerated failure was brought about by the combined effects of moisture and temperature. It was documented that moisture effects were enhanced as temperature increased [17], and that composite property temperature sensitivity was magnified by increases in moisture [25]. This leads to the conclusion that the effects of heat and moisture are mutually degenerative to the mechanical properties of composite structures.

Rothchilds, *et. al.* [37], asserted that matrix cracking can affect both matrix- and fiber-dominated properties. Hygrothermal effects strongly influence matrix crack formation on both a micro and macro scale. The differences in temperature and moisture expansion properties between the fiber and matrix result in residual stresses in the laminate. They have found that Kevlar/epoxy was more susceptible to environmental conditions than carbon/epoxy and glass/epoxy laminates. This was due to the large mismatch of thermal coefficients for the Kevlar/epoxy composite. However, Kevlar/epoxy had reasonably good resistance to matrix cracking due to its low transverse modulus.

The combined effects of temperature and moisture may also aid in the formation of larger voids during hygrothermal conditioning. As temperature increases, the thermal expansion mismatch between fiber and matrix allows voids and microgaps to grow. Moisture is able to settle in these areas causing swelling of the matrix and further stress damage. This process allows diffusion of moisture into the composite at a faster rate [27]. The presence of voids in composite materials result in diminution of mechanical properties.

It appears that the presence of braided fibers in a resin matrix may promote the hygrothermal failure mechanisms discussed above. Once again, the characteristically high amount of interior voids present in a braided structure may adversely affect its performance in hygrothermal environments. Kevlar fibers are burdened with the additional onus of having particularly poor bonding characteristics [38].

Saunders [8] conducted mechanical tests of braided $\pm 45^0$ E-glass/epoxy and braided $\pm 90^0$ glass, Kevlar, and carbon/epoxy composites at room temperature and 350^0F. Degradation in tension, compression and shear strength was apparent for all materials tested at the higher temperature. No specific reason was given for this adverse affect of temperature. He found, however, that braided glass and Kevlar composites had roughly the same strength values as most comparable woven specimens. Braided carbon, on the other hand, displayed a marked decrease in mechanical properties over woven carbon products.

The environmental effects on woven Kevlar/epoxy and Kevlar/thermoplastic composites were examined by Khan [31]. All specimens were aged at 180^0F in 80 percent relative humidity for 21 days. He found that hot and humid aging had a detrimental effect on flexural properties of thermoset (epoxy) composites. Thermoplastic composites displayed better flexural properties, both in terms of absolute and percent retention after conditioning, than comparable thermoset composites.

The effect of hot and wet aging of braided fiber reinforced epoxy composites appears to be substantial. In some cases, due to large void volumes, degradation may be worse than that in comparable angle-plied composite laminates. Braided composite properties do not seem to escape hygrothermal detrimental effects.

The prediction of hygrothermal effects on braided composites is difficult. In this review, no attempt is made to establish quantitative predictions. Only broad conclusions are reached and qualitatively discussed.

2.4 Summary

Major test results and conclusions pertaining to braided composites are summarized in Table 1. Tensile strength and tensile modulus data on hygrothermally affected composites (including some data from Table 1), are shown in Table 2. It is important to note that values are only indications of behavior. Direct comparisons are generally not advisable due to variations in fiber volume fraction, void content and resin systems.

3 EXPERIMENTAL EQUIPMENT AND PROCEDURES

3.1 Composite Specimens

The composite materials considered in this study are S-2 glass fiber reinforced epoxy, Kevlar fiber reinforced epoxy, carbon fiber reinforced epoxy, and sandwich composites consisting of both Kevlar and carbon fibers. Additionally, certain composites have stainless steel foil and rubber inhibitor adhered to one side. For ease of reference, all candidate materials, lettered A through L, are listed in Table 3. Appendix A describes specimen properties and fabrication procedures.

3.2 Testing Procedures

Mechanical and material characteristics are conducted on candidate composite specimens. The test matrix for this research is summarized in Table 4. As indicated, tensile strength and tensile modulus are determined for both unconditioned specimens and specimens conditioned via exposure to a 560^0F environment for one second at ambient humidity. A schematic of a typical tensile specimen is shown in Fig. 2. Material characteristics are observed after exposure to slow and fast heating rates (slow and fast cook-off, respectively). In addition to controlling the rate of heating, cook-off tests control the maximum temperature reached and the time of exposure. Detailed testing procedures and equipment are described in Appendix B.

3.2.1 Width Effects Determination

Test specimen width is important in determining reliable tensile properties. This is especially true in light of Crane and Camponeschi's findings that braided

specimens cut from larger panels are susceptible to significant reductions in ultimate tensile strength over specimens braided to exact test widths [12]. Therefore, width effect testing precedes tensile testing.

Representative samples of $\pm 65^0$ triaxially braided Kevlar fiber reinforced epoxy (Material C) are used to determine the minimum width required for tensile testing. Storage and testing are conducted at room temperature and humidity. Widths that are too small result in unreliably low test results. This is a function of edge effects and load-carrying capability of angled fibers in the braid. Above a given width, the measured tensile strength of the specimens is constant. Hence, this minimum width is used for all braided material tensile tests.

3.2.2 Tensile Tests

Specimens are tested to failure. Use of an extensometer and plotter provides modulus data. Ultimate load data are read directly from the Materials Testing System (MTS) tensile tester in volts and then converted to pounds force. Ultimate tensile strength is determined by dividing the maximum force by the specimen cross-sectional area prior to the test.

3.2.2.1 Room Temperature Tests

Measurement of tensile strength at room temperature duplicates those conditions most likely to be encountered during storage of pressure vessels. Information regarding the strength of the specimens at room temperature gives useful data about the materials to be used in the final vessel design. Additionally, these data are used to form a baseline. Comparison of elevated-temperature conditioned tests to the baseline allows conclusions to be derived regarding temperature effects on strength.

Specimens are stored and tested at room temperature and humidity, typically 70^0F and 50 percent relative humidity. No special conditioning is undertaken prior to testing.

3.2.2.2 Elevated Temperature Conditioning

Elevated-temperature conditioning tests yield a measurement of tensile strength after exposure to environments more severe than ambient conditions. Comparison of environmentally-conditioned test results with room temperature results may generate a multiplicative factor allowing the prediction of post-conditioning performance.

Elevated-temperature conditioning is conducted through the use of an environmental chamber. A photograph of the chamber is included as Fig. 3. The specimens are placed in a constant 560^0F environment for one second and are then cooled at the specified rate given in Fig. 4. Temperature in the environmental chamber is monitored with a thermocouple.

3.2.3 Cook-Off Testing

Slow and fast cook-off tests are performed to analyze the characteristics of the material when subjected to relatively low-temperature prolonged heat, and relatively high-temperature intense heat of short duration.

3.2.3.1 Slow Cook-Off

Slow cook-off tests approximate the effects of exposure to slowly increasing temperatures on the material being tested. Visible char suggests loss of strength. In pressure vessels, it may be desirable that case materials lose their ability to hold pressure before temperatures causing an explosion of the contents are reached. Slow

cook-off data are an indication of the resistance of the specimen to slowly increasing temperatures. These types of temperatures may be found in storage areas under abnormally hot operational conditions.

Slow cook-off tests are conducted in a 2192^{0}F Lindberg Model 51442 Muffle Furnace at temperatures of 237.50^{0}F, 356.25^{0}F and 475.00^{0}F. The specimens are exposed to the elevated temperatures for a period of one hour. After the specified time, the samples are removed and are qualitatively examined. It is not within the scope of this research to determine residual elastic properties of materials subjected to slow cook-off environments.

3.2.3.2 Fast Cook-Off

Determination of the response of case materials to rapidly rising temperatures is accomplished through fast cook-off testing. These types of environments are likely to be encountered in only the most extreme conditions. Service use and contents of the pressure vessel dictate the desired properties of the material. Graceful degradation may be preferred to properties allowing the structure to withstand extreme environments.

Fast cook-off tests are conducted using an oxyacetylene torch and a 1999^{0}F K-type Chromel-Alumel thermocouple. Fig. 5 is a schematic of the testing set-up. The samples are subjected to the flame in a ventilated hood approved for toxic substances.

Surface temperature of the composite samples reach 1000^{0}F within the first 30 seconds, and average 1500^{0}F for the remainder of the test. A sacrificial sample of Material J is used to calibrate the required flame distance from the specimen.

The test is undertaken for a period of no more than 15 minutes. If a sample has obviously lost its ability to support any load prior to the end of 15 minutes, the test is stopped and the time is noted. All samples are qualitatively examined at one-minute intervals throughout the testing.

4 RESULTS AND DISCUSSION

Results for width effect determination, tensile testing, and cook-off testing were obtained using the test matrix outlined in Table 4. Data for width effect and tensile tests are presented in Appendix C.

4.1 Width Effects Determination

Three specimens of Material C were tested at four widths: 1 inch, 1.25 inches, 2 inches, and 3 inches. Material C was chosen because its braid angle of $\pm 65^0$ was midway between the minimum ($\pm 55^0$) and maximum ($\pm 75^0$) braid angles to be tested in the tensile test portion of this research. The desire to conserve test material and the limitation of 4 inch maximum widths for the MTS wedge grips precluded testing specimens of larger widths. The test widths were chosen to optimize material usage and to obtain a broad range of widths for comparative purposes.

Table 5 summarizes tensile strength data of material C for width effects determination. Fig. 6 is a graphical representation of these data. The testing showed that as specimen widths increased, ultimate tensile strength (UTS) increased sharply and then leveled off to a relatively constant value. The minimum width at which UTS began to show consistency was chosen as the tensile test specimen width. Thus, tensile test specimens were standardized at a width of 2 inches.

4.2 Tensile Tests

Tensile testing was conducted on materials A through K to obtain UTS and tensile modulus data. Specimen failure was marked by a distinctive decrease of load-carrying capacity in all tests. Figs. 7 through 11 show representative samples of the tested materials after failure. Elevated temperature exposure at 560^0F for one

second had no visual effect of specimen failure. Therefore, the samples shown in Figs. 7 through 11 are typical tensile ruptured specimens (room temperature or elevated temperature conditioned at 560^0F). All tensile tests were conducted satisfactorily with the exception of Material K. The rubber inhibitor attached to Material K delaminated prior to tensile failure of the specimen. Because of this delamination, UTS could not be obtained. Tensile modulus, however, was calculated from the initial slope of the load versus strain curve.

Examination of data presented in this section should be undertaken with the appreciation that each material possesses different values of fiber volume fraction. Emphasis for this research was placed on testing material systems "as-received" from the manufacturer. Advantages and disadvantages of materials are therefore compared between actual alternatives, rather than theoretical specimens. Although the calculations were not conducted for this research, it is possible to normalize UTS and tensile modulus values to a common fiber volume fraction.

The number of material configurations, braid angles, and laminate plies incorporated in this research results in a large array of comparative possibilities between material systems. Three areas of interest were chosen to simplify the comparative process: braid angle effects, dual-ply effects, and multi-ply effects. Summaries of comparisons made between material systems are included in Tables 6 and 7. The vertical axis of Table 7 represents the baseline material for comparative purposes. The format shown in Table 7 is used for room temperature and elevated temperature conditioned specimens.

4.2.1 Room Temperature Tests

Room temperature tensile testing yielded UTS and tensile modulus data as summarized in Table 8. A summary of percent differences of UTS between baseline materials and material systems of interest is included in Table 9. Tensile modulus data are compared in Table 10.

4.2.1.1 Braid Angle Effects

In single-ply triaxially braided composites of the same fiber and matrix constituents, UTS and tensile modulus decreased as braid angle increased. This result was expected since at higher braid angles, radial hoop strength and stiffness are enhanced by the reinforcing fibers at a cost to longitudinal strength and stiffness. The fabrication process involved in manufacturing the triaxially braided specimens is also a factor in determining UTS and tensile modulus. As the braid angle increases, the number of 0^0 fibers decreases for a fixed specimen width.

The change in tensile strength as a function of braid angle for single-ply specimens differed for Kevlar/epoxy and glass/epoxy materials. However, both material E and material F (with braid angles of $\pm 75^0$) showed the same 59 percent reduction in tensile strength compared to materials A and B (with braid angles of $\pm 55^0$), respectively.

The rate of decrease of tensile modulus was greater for single-ply Kevlar/epoxy materials than for single-ply glass/epoxy materials. As Table 10 shows, material E (single-ply Kevlar/epoxy braided to $\pm 75^0$) degraded nearly twice as much as material F (single-ply glass/epoxy braided to $\pm 75^0$) when compared to their respective baseline materials A and B, respectively.

In most cases, failure of the specimens was characterized by cracking of the composite along the braid angle. Braided fiber crossover points are susceptible to localized strength reduction. As fibers cross over each other in the braid, small radii of curvature may result, inducing a significant bending stress in the fiber. Kevlar fibers are especially prone to strength degradation in bending. Hull [45] showed that for Kevlar 49 fibers subjected to bending, permanent yielding occurred on the compressive side of the fiber long before the curvature was sufficient to cause tensile failure of the fiber.

The probability of matrix void formation is higher at fiber crossover points. The extremely close proximity of fibers at areas of fiber crossover may preclude total coverage of the fibers by the resin. Since loads are not transferred through a void, stress concentrations develop around the void, resulting in a locally weaker structure.

Tensile failure of specimens is also affected by the $\pm\theta$ (wrap) fibers within a braid which tend to rotate under applied tensile loads so they become more aligned with the axis of loading. The shear developed within the lamina by fiber rotation results in an intralaminar shear effect that may weaken the composite. Within a braided composite containing interwoven $\pm\theta$ fibers, the intralaminar shear effect is magnified because the direction of $+\theta$ fiber rotation directly opposes the tendency of $-\theta$ fiber rotation.

Tensile strength and tensile modulus for single-ply glass/epoxy materials were greater than those for single-ply Kevlar/epoxy materials at all braid angles.

As the "rule of mixtures" for unidirectional composite laminae shows, UTS is a function of constituent fiber properties. The underlying theory of the "rule of mixtures" can be extended to the braided materials of this study. Table 11 shows

that S-2 glass fibers are 27 percent stronger in tension than Kevlar 49 fibers and 33 percent stronger in tension than Kevlar 149 fibers. The higher tensile strength of the glass fibers is reflected in the greater UTS of glass/epoxy materials compared to their Kevlar/epoxy counterparts.

The reported tensile modulus of the fibers, however, is in disagreement with experimental values obtained for composite specimens. Experimentally determined values of tensile modulus for Kevlar/epoxy materials were, in general, lower than tensile modulus values for glass/epoxy materials. Determination of tensile modulus for the composite specimens was based on the initial slope of the load versus strain curve. It is possible that in the initial region of the curve, strain measurements were artificially high, as slack in the braid was being removed by progressive loading. This explanation for imprecise tensile modulus measurements would have had more effect on the Kevlar specimens than the glass specimens due to decreased fiber-epoxy bonding inherent in Kevlar/epoxy composites. Therefore, the true Kevlar/epoxy tensile modulus which could be achieved in a cylinder may be greater than reported in Table 10, thus reflecting the higher modulus of the individual Kevlar fibers over that of S-2 glass fibers.

Important to the discussion of tensile test results is the fact that, in general, glass/epoxy single-ply specimens were resin rich and Kevlar/epoxy single-ply materials were resin starved. Lack of resin coverage in the Kevlar/epoxy samples may have played a significant role in the outcome of reported results.

A certain degree of "waviness" of the braid was observed in all test specimens. Ideally, the third, triaxially braided (warp) fiber should have been aligned in the 0^0 direction for the entire length of the test specimen. In reality, deviations of up to several degrees were noticed on several specimens. Glass/epoxy materials were

more prone to this "waviness" than Kevlar/epoxy materials. Since the "waviness" was more pronounced in the glass/epoxy materials and these materials possessed better tensile properties than the Kevlar/epoxy materials, it might be assumed that, in general, glass/epoxy is even more superior to Kevlar/epoxy than reported here. In any event, the extent to which this "waviness" degraded the material properties is unclear; however, it is not believed to be significant.

4.2.1.2 Dual-Ply Effects

Increased thickness of two-dimensional braided composites is accomplished by incorporating additional plies into the material. Thus, a dual-ply braided composite consists of two laminae of single-ply lamina.

Material G (dual-ply Kevlar/epoxy) displayed modest increases in tensile strength and tensile modulus compared to the corresponding single-ply braided Kevlar/epoxy material C. On average, tensile strength and tensile modulus of material G increased 8 percent over material C. The modest increase in tensile properties of material G is thought to be due to the addition of the 90^0 stainless steel foil strips to the composite. (Theoretically, the 1.25 inch wide strips which were orthogonal to the tensile axis should have no effect on tensile properties.)

The dual-ply glass/epoxy materials showed much greater improvement in tensile properties than the dual-ply Kevlar/epoxy specimens. The UTS of material H (dual-ply glass/epoxy) increased 103 percent and the tensile modulus increased 26 percent over its corresponding single-ply system, material D. These increases in tensile properties are not due solely to the 90^0 stainless steel foil strips adhered to one side of the composite.

Tensile properties of the dual-ply glass/epoxy (material H) were not expected to increase so significantly over those of single-ply glass/epoxy (material D). The increase is due possibly to better interlaminar adhesion properties of the laminae in the glass/epoxy system compared to the Kevlar/epoxy system. Thus, load-sharing capabilities could be enhanced within the entire structure, resulting in increased tensile properties.

Failure mechanisms leading to increased UTS values for material H may also offer a plausible explanation. During testing, Kevlar/epoxy materials had the tendency to exhibit audible cracking sounds under progressive loading. This was thought to be due to cracking along the fiber-matrix interface as slack was being removed from the braid. The crack formation in the Kevlar/epoxy material could have caused premature failure of the samples, since load sharing may have been reduced at an early stage of testing. Glass/epoxy materials did not, in general, exhibit as much audible cracking noise during tensile testing as the Kevlar/epoxy specimens. Hence, fiber/matrix loading may have been more nearly ideal in material H compared to material G.

Void content of the single-ply glass/epoxy materials may have been higher than the corresponding dual-ply specimens. This interpretation would imply that the tensile properties of the single-ply materials were degraded, resulting in an apparent improvement of dual-ply UTS and tensile modulus.

It is most likely that the differences in tensile properties between the single-ply and dual-ply composites are the result of a combination of effects described in the previous explanations. Regardless, it can be stated that in general, dual-ply materials

displayed improved tensile strength and tensile modulus over their single-ply counterparts. In particular, glass/epoxy dual-ply material H showed marked improvements compared to Kevlar/epoxy dual-ply material G.

4.2.1.3 Multi-Ply Effects

Tensile strength of the composite sandwich material J is computed to be 81,155 psi via the "rule of mixtures" (using materials G and I as constituent materials). The actual UTS of material J was experimentally determined to be 55,394 psi. The difference between the computed value and the actual value of UTS is 32 percent. This disparity in UTS is partially explained by the lack of foil and film in material J.

Due to delamination of the rubber inhibitor prior to failure on material K, UTS data are not available. The tensile modulus, however, was calculated from the initial slope of the load versus strain curve. The data showed that tensile modulus of material K (Kevlar/epoxy-carbon/epoxy-Kevlar/epoxy-steel foil-rubber inhibitor sandwich) was greater than material G (dual-ply Kevlar/epoxy) by 183 percent. By comparison, the tensile modulus of material J (Kevlar/epoxy-carbon/epoxy-Kevlar/epoxy-steel foil sandwich) was larger than the tensile modulus of material G by 261 percent. The smaller increase exhibited by material K is possibly due to the incorporation of the rubber inhibitor (in material K) to which the tabs were attached.

4.2.2 Elevated Temperature Conditioning

Materials conditioned via exposure to a 560^{0}F environment for one second at ambient humidity were tensile tested to determine UTS and tensile modulus. UTS

data for material K were unattainable because of inhibitor delamination as in the room temperature tests. Table 12 summarizes data for UTS and tensile modulus of materials A through K. A summary of percent differences of UTS between baseline materials and other materials is shown in Table 13. Tensile modulus differences are compared in Table 14. Table 15 compares UTS and tensile modulus for room temperature and elevated temperature conditioned specimens.

4.2.2.1 Braid Angle Effects

Single-ply braided composites of both glass/epoxy and Kevlar/epoxy showed decreases in UTS and tensile modulus for corresponding increases in braid angles. The change in UTS as a function of braid angle differed for Kevlar/epoxy and glass/epoxy materials. Tensile strength degradation of material E (single-ply Kevlar/epoxy braided to $\pm 75^0$) was 64 percent compared to its $\pm 55^0$ braided counterpart, material A. Material F (single-ply glass/epoxy braided to $\pm 75^0$), degraded only 55 percent compared to the $\pm 55^0$ braided single-ply glass/epoxy material B.

Graphical comparison of UTS as a function of braid angle for all single-ply systems is presented in Fig. 12. Exposure to a 560^0F environment for one second resulted in mixed effects on the UTS of single-ply materials. At a braid angle of $\pm 55^0$, the 560^0F exposure degraded glass/epoxy, but increased Kevlar/epoxy UTS. The reverse trend was seen at a braid angle of $\pm 65^0$; glass/epoxy UTS improved after 560^0F exposure, while Kevlar/epoxy strength was reduced. These increases and decreases may not be statistically significant. At a braid angle of $\pm 75^0$, virtually no difference was seen in UTS of any materials as a result of 560^0F exposure.

Tensile modulus data are graphically compared in Fig. 13. The data show that, in general, Kevlar/epoxy single-ply materials degrade faster than glass/epoxy

single-ply materials for increasing braid angles. The rate of degradation of Kevlar/epoxy and glass/epoxy materials was not altered greatly after exposure to a 560^{0}F environment for one second.

4.2.2.2 Dual-Ply Effects

Compared to single-ply glass/epoxy materials exposed to a 560^{0}F environment for one second, UTS of the corresponding dual-ply material H exposed to the same elevated temperature condition more than doubled. The same mechanism responsible for the 2 to 1 increase observed in room temperature tests is believed to cause the similar results for specimens exposed to the 560^{0}F environment. As in the room temperature tensile tests, the glass/epoxy dual-ply composite, material H, had over twice the UTS measured for its Kevlar/epoxy counterpart, material G.

UTS and tensile modulus data of the dual-ply composites are presented in Figs. 14 and 15. Fig. 14 shows that after exposure to 560^{0}F for one second, UTS for the glass/epoxy dual-ply material H increased slightly. The UTS of the Kevlar/epoxy dual-ply material G also improved slightly after exposure to 560^{0}F for one second.

4.2.2.3 Multi-Ply Effects

Use of the "rule of mixtures" gives a tensile strength of the composite material J, after exposure to a 560^{0}F environment for one second, of 81,775 psi. The experimentally determined tensile strength for the same material was 53,341 psi. The difference between the estimated UTS and the actual UTS is 35 percent. These results are similar to those found for room temperature tests. Exposure to the 560^{0}F environment had little effect on UTS and tensile modulus properties of the multi-ply composites as seen in Figs. 16 and 17. The lack of response could be due to the

thickness of the specimens. Since exposure to the 560^{0}F environment was limited to one second, the heating may have had negligible effect on the material properties reported here.

4.3 Cook-Off Testing

Cook-off tests were conducted in accordance with Table 4. Single-ply specimens were represented by materials C and D since braid angle was not expected to play a role in either slow or fast cook-off tests. Material L was chosen over material K for testing because it was felt that the rubber inhibitor of material K was unnecessary for obtaining accurate results.

4.3.1 Slow Cook-Off

Fig. 18 is a photograph showing the effects of slow cook-off testing on the materials examined in this portion of the research. Table 16 qualitatively summarizes the effects of slow cook-off testing.

Exposure at 237.50^{0}F for one hour had little effect on the test specimens. In most materials, this elevated temperature produced no visible effects. Single-ply glass/epoxy material D, on the other hand, displayed increased stiffness when flexed by hand compared to virgin material D. Sandwich materials J and L were observed to display better heat retention properties after exposure to 237.50^{0}F for one hour than the other materials tested.

Mild to moderate discoloration of all specimens occurred after slow cook-off testing at 356.25^{0}F for one hour. A visible change in the epoxy was evident in Material I (unidirectional carbon/epoxy). Because T_g of the resin used in the materials is 270^{0}F, the one hour testing time produced changes in the material characteristics of the tested specimens.

All specimens tested at 475.00^{0}F for one hour showed marked signs of discoloration and material changes. Material C (single-ply Kevlar/epoxy) displayed signs of becoming more ductile in flexure than virgin material C, while material D (single-ply glass/epoxy) became stiffer than virgin material D. Discoloration was visible on all samples, indicating that material properties were being affected by the elevated temperature. Carbon/epoxy material I became weaker in flexure compared to both virgin material I samples and material I specimens tested at lower temperatures.

In all cases, the effects of increasing temperature for the same time period resulted in more severe changes to material appearance. In materials that showed signs of becoming flexurally weaker or stronger after heating at lower temperatures, the effects were intensified after higher temperature exposure.

4.3.2 Fast Cook-Off

Fast cook-off testing on material systems of interest resulted in dramatic changes in material characteristics. Table 17 summarizes fast cook-off effects for each material at one minute intervals. Fig. 19 is a photograph comparing virgin specimens with materials subjected to fast cook-off testing.

Single-ply specimens were least effective at retaining their structural integrity under intense heating conditions. Material C (single-ply Kevlar/epoxy) lasted less than 15 seconds before the epoxy was burned away and all fibers in the flame path were consumed. Material D (single-ply glass/epoxy) was able to withstand testing for approximately three minutes. Unlike the Kevlar/epoxy material, the glass/epoxy specimen fibers were not consumed by the flame. Loss of structural integrity in material D occurred by burning away of the epoxy.

Dual-ply specimens were more resistant than single-ply materials subjected to fast cook-off testing. Materials G and H both maintained structural integrity twice as long as their single-ply counterparts. Otherwise, the failure characteristics were similar.

Multi-ply specimens displayed the most resistance during heat application. Material L lasted the entire test period without totally losing structural integrity. The resistance of material L to intense heat is due to the many layers present in the composite. Further, the carbon/epoxy constituent provided the strongest barrier to thermal degradation.

Material L outlasted material J by five minutes during fast cook-off testing. The only difference between the two materials was the presence of foil and film on material L. The adhesion of this foil and film caused a reinforcement of the composite structure not experienced by material J.

4.4 Summary

A summary of relative performance characteristics of all materials tested is presented in Table 18. The descriptions, "Excellent", "Good", "Moderate", and

"Poor" used in Table 18 are relative qualitative assessments which are intended for comparisons between materials considered in this research, and should not be regarded as descriptions for comparisons with other materials.

Materials regarded as "Excellent" exhibited properties far superior to all other materials tested under the same conditions. The vastly improved tensile properties of carbon/epoxy and the resistance to intense heat of the Kevlar/epoxy-carbon/epoxy-Kevlar/epoxy-steel foil sandwich material L are examples of materials with "Excellent" ratings.

The "Good" description refers to materials that were marginally better than most materials subjected to the same testing conditions. These materials showed potential for improved performance under different configurations and testing conditions.

Those materials designated "Moderate" showed properties that were marginally worse than most materials subjected to the same testing conditions. These materials showed little potential for improved performance under different configurations and testing conditions.

The "Poor" rating was reserved for specimens that displayed unsatisfactory performance compared to the other materials under similar testing conditions. These materials showed no potential for improvement in their current configuration.

5 CONCLUSIONS

Twelve different material systems, designated materials A through L (Table 3), were examined in this research. Tensile strength and tensile modulus of the composite specimens were experimentally determined. Cook-off tests were conducted on selected specimens to qualitatively assess their resistance to heat.

Based on the tests conducted on materials A through L, the following conclusions can be made:

1. Results obtained during the width effects determination testing showed that as the nominal cut width of specimens increased, average ultimate tensile strength (UTS) increased and then leveled off to a relatively constant value. Two (2) inches represents an acceptable width for tensile specimens of braided fiber reinforced epoxy materials when the braid angle is in the range of 55^0 to 75^0.

2. For all single-ply braided composite materials tested, UTS and tensile modulus were functions of braid angle. As braid angle increased, UTS and tensile modulus decreased.

3. Tensile testing showed that for the same braid angle, glass/epoxy braided single-ply composites retained constituent tensile properties better than their Kevlar/epoxy counterparts.

4. Dual-ply braided glass/epoxy material H displayed a 103 percent improvement in UTS compared to its single-ply counterpart, material D. Dual-ply braided Kevlar/epoxy material G displayed an 8 percent improvement in UTS compared to its single-ply counterpart, material C.

Manufacturing procedures, void content and inherent wetting characteristic differences between glass/epoxy and Kevlar/epoxy may have caused the large disparity in tensile strength improvement of dual-ply glass/epoxy over dual-ply Kevlar/epoxy.

5. Use of the "rule of mixtures" provides an estimate of theoretical values for tensile strength and tensile modulus of materials in a composite sandwich configuration.

6. Exposure for one second to a 560^0F temperature prior to tensile testing produced minor improvements of tensile properties in some material configurations and minor degradation in others.

7. One-hour exposures to temperatures of 237.50^0F, 356.25^0F and 475.00^0F produced varying degrees of discoloration of the specimens. Discoloration implies changes in material properties and degradation of mechanical properties.

8. Single-ply and dual-ply Kevlar/epoxy materials exhibited the poorest resistance to fast cook-off testing, while multi-ply Kevlar/epoxy-carbon/epoxy-Kevlar/epoxy materials displayed the greatest resistance to intense heat.

9. The addition of stainless steel foil strips adhered by bonding film to multi-ply materials produces a supporting structure, thus increasing the composite's ability to retain structural integrity during intense heat.

6 RECOMMENDATIONS

This research examined material and mechanical characteristics of selected advanced composite materials. The recommendations presented below focus on potential extensions, improvements and verifications of the experimental results obtained in this study.

6.1 Width Effect Determination

Little work has been undertaken to understand the effects of cutting braided composite materials to specimen dimensions versus braiding the structure to exact dimensions. As fabrication procedures are improved, designers will have the option of choosing "braided-to-width" materials over "cut-edge" materials. Increased understanding of width effects is highly desirable for ensuring the proper test procedures to obtain accurate constitutive data.

6.2 Tensile Testing

The mechanical tests in this research were limited to tensile strength and tensile modulus of selected composite materials. Based on the tests conducted, the following investigations are recommended:

1. Hygrothermomechanical effects on transverse tensile strength, tensile modulus, interlaminar shear strength and flexural properties should be assessed to more fully understand temperature and moisture effects.

2. The finding that the dual-ply braided glass/epoxy displayed greatly improved tensile properties compared to the single-ply braided glass/epoxy material should be investigated to determine the underlying mechanisms.

3. To fully appreciate the effects of elevated temperature conditioning on tensile properties, composite specimens should be tested at elevated temperatures using an environmental chamber.

4. Tests on full-scale cylindrical pressure vessels should be performed to verify results developed from testing flat specimens.

6.3 Slow Cook-Off Tests

Based on the slow cook-off tests conducted, the following recommendations are made:

1. Slow cook-off tests should be conducted for longer periods of time to replicate harsh environments and determine trends of degradation.

2. Slow cook-off tests should be conducted over a larger array of temperatures and times to investigate the effect of time at a given temperature.

3. Quantitative slow cook-off observations should be made by conducting mechanical testing of post-conditioned specimens.

6.4 Fast Cook-Off Tests

The fast cook-off experiments were conducted to gain qualitative insight into the mechanisms of high-temperature composite degradation. These tests can be improved in the following ways:

1. Tests should be conducted with an improved method of surface temperature control. Variations in flame distance from the test specimen as small as one inch can change surface temperatures by several hundred degrees.

2. Fast cook-off tests should be performed on multiple samples of the same materials to improve predicted times of structural integrity retention.

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TABLE 1 Literature Review of Mechanical Properties of Various Configurations of Braided Composite Materials.

Material	Configuration	Braid Angle (degrees)	Tensile Strength (ksi)	Tensile Modulus (Msi)	Notes	Ref.
Glass/epoxy	Two-dimensional	±45 ±45	25 11	- -	a b	[8]
Glass/epoxy	Two-dimensional	0,90 0,90	54 36	- -	 b	[8]
Kevlar/epoxy	Two-dimensional	0,90 0,90	65 30	- -	 b	[8]
Carbon/epoxy	Two-dimensional	0,90 0,90	66 44	- -	 b	[8]
Carbon/epoxy	Three-dimensional [1 x 1] Braid	21.1 ±2.1	185 ±25	15.3 ±2.3		[10]
Carbon/epoxy	Three-dimensional [1 x 1] uncut [1 x 1] cut	 ±20 ±20	 96.5 33.2	 14.2 7.3		[12]
Carbon/epoxy	Three-dimensional [3 x 1] uncut [3 x 1] cut	 ±12 ±12	 141 52.7	 18.3 11.1		[12]

(Continued on next page)

- Indicates data not given in reference.

a All specimens are tested at room temperature and humidity unless indicated otherwise.

b Specimens tested at 350^{0}F.

TABLE 1 (Continued) Literature Review of Mechanical Properties of Various Configurations of Braided Composite Materials.

Material	Configuration	Braid Angle (degrees)	Tensile Strength (ksi)	Tensile Modulus (Msi)	Notes	Ref.
Carbon/epoxy	Three-dimensional [1 x 1]1/2 Fixed uncut [1 x 1]1/2 Fixed cut	 ±15 ±12	 115 58.9	 17.0 12.0		[12]
Glass/epoxy	Three-dimensional	c	107	2.02		[13]
Carbon/epoxy	Three-dimensional	±12 to 14.5 ±13.5 ±13 to 15	189 173 199	16.6 15.3 15.4		[14]
Carbon/epoxy	Three-dimensional [1 x 1]	±12 ±15 ±15 ±17.5	155 120 128 178	- - - -		[39]
Carbon/epoxy	Three-dimensional [1 x 1]	 ±70	 5	 -		[40]
Carbon/epoxy	Two-dimensional Triaxial braid cylinder	±45 ±63	- -	8.9 7.1		[15]
Carbon/epoxy	[1 x 1] Braid [1 x 1] 1/2 Fixed	c c	96.8 109	13.1 15.4		[41]

- Indicates data not given in reference.

c Braid angle not explicity given in reference.

TABLE 2 Summary of Literature on Hygrothermomechanical Effects on Tensile Properties of Composites.

Material	Configuration	Treatment	Effect after Treatment		Notes	Ref.
			Tensile Strength	Tensile Modulus		
Glass/epoxy	Two-Dimensional Braid $\pm 45^0$ $0^0,90^0$	 Tested at 350^0F[a] Tested at 350^0F[a]	 -56% -33%	 - -	b	[8]
Kevlar/epoxy	Two-Dimensional Braid $0^0,90^0$	 Tested at 350^0F[a]	 -54%	 -		[8]
Carbon/epoxy	Two-Dimensional Braid $0^0,90^0$	 Tested at 350^0F[a]	 -33%	 -		[8]
Glass/epoxy	$[0_{16}]$	75^0F 0% RH, 1 Month 50% RH, 3 Months 95% RH, 3 Months 160^0F 95%RH, 1 Month	 Baseline -2.5% -23.8% -38%	 Baseline -0.9% -0.3% +0.9%		[42]

(Continued on next page)

- Indicates data not given in reference.

a Conditioning time not given.

b Baseline values for all tests are ambient conditions (that is, room temperature, atmospheric pressure and less than 30% relative humidity) unless otherwise noted.

RH Indicates relative humidity.

TABLE 2 (Continued) Summary of Literature on Hygrothermomechanical Effects on Tensile Properties of Composites.

Material	Configuration	Treatment	Effect after Treatment		Notes	Ref.
			Tensile Strength	Tensile Modulus		
Glass/epoxy	$[0/+45/-45/90]_s$	75^0F 0% RH, 1 Month 50% RH, 3 Months 95% RH, 3 Months 160^0F 95%RH, 1 Month	 Baseline +1.7% -15.4% -35%	 Baseline +1.4% +6.6% +9.4%		[42]
Carbon/epoxy	c	Tested at 70^0F[a] Tested at 302^0F[a]	Baseline -29%	- -		[43]
Carbon/epoxy	$[0_6]$	0% Moisture[a] 72^0F 140^0F 196^0F 1% Moisture[a] 72^0F 196^0F	 Baseline -6.6% -3.4% -8.9% -4.3%	 Baseline -1.8% -5.0% -3.2% +3.2%	Low Strain Rate: (10^{-6} s^{-1})	[18]

(Continued on next page)

- Indicates data not given in reference.

a Conditioning time not given.

c Configuration not explicitly given in reference.

TABLE 2 (Continued) Summary of Literature on Hygrothermomechanical Effects on Tensile Properties of Composites.

Material	Configuration	Treatment	Effect after Treatment		Notes	Ref.
			Tensile Strength	Tensile Modulus		
Carbon/epoxy	$[0_6]$	0% Moisture[a]			High Strain Rate: ($5\ s^{-1}$)	[18]
		72°F	Baseline	Baseline		
		140°F	+0.9%	+3.8%		
		196°F	+2.9%	+5.6%		
		1% Moisture[a]				
		72°F	-5.6%	+1.4%		
		196°F	-5.9%	0%		
Carbon/epoxy	$[0_8]$	0.1% Moisture			d	[20]
		75°F	Baseline	-		
		0.7% Moisture				
		75°F	+3.1%	-		
		165°F	+13.1%	-		
		205°F	+15.9%	-		
		1.15% Moisture				
		75°F	+20.6%	-		
		205°F	+24.6%	-		

(Continued on next page)

- Indicates data not given in reference.

a Conditioning time not given.

d All specimens conditioned 30 days.

TABLE 2 (Continued) Summary of Literature on Hygrothermomechanical Effects on Tensile Properties of Composites.

Material	Configuration	Treatment	Effect after Treatment		Notes	Ref.
			Tensile Strength	Tensile Modulus		
Carbon/epoxy	$[0_6]$	250°F, 1 atm. 350°F, 1 atm. 350°F, 2 psi	0% -39% -24%	- - -	e	[21]
Carbon/epoxy	$[0,\pm45]_s$	250°F, 1 atm. 350°F, 1 atm. 350°F, 2 psi	-44% -46% -31%	- - -	e	[21]
Neat epoxy resin	c	Water Immersion 158°F, 20 days	-33%	-45.2%		[27]
Glass/epoxy	Unidirectional Bidirectional Chopped-Strand Mat	Water Immersion 158°F, 20 days	-8% -13.7% -20.4%	-5% -14.6% -24%		[27]
Carbon/epoxy	c	Water Immersion 158°F, 20 days	-12.8%	-8.9%		[27]

(Continued on next page)

- Indicates data not given in reference.

c Configuration not explicitly given in reference.

e All specimens aged for 5.7 years and tested at 350°F.

TABLE 2 (Continued) Summary of Literature on Hygrothermomechanical Effects on Tensile Properties of Composites.

Material	Configuration	Treatment	Effect after Treatment		Notes	Ref.
			Tensile Strength	Tensile Modulus		
Kevlar/epoxy	c	Water Immersion 158°F, 20 days	-12%	-32.5%		[27]
Glass/Carbon/ epoxy	c	Water Immersion 158°F, 20 days	-13.1%	-13.5%		[27]
Carbon/Kevlar/ epoxy	c	Water Immersion 158°F, 20 days	-7.5%	-8.5%		[27]

c Configuration not explicitly given in reference.

TABLE 3 List of Candidate Materials in Test Program.

Designation	Plies	Angle	Configuration	Constituents
A	1	$\pm 55^0$	Triaxial Braid	Kevlar/epoxy
B	1	$\pm 55^0$	Triaxial Braid	Glass/epoxy
C	1	$\pm 65^0$	Triaxial Braid	Kevlar/epoxy
D	1	$\pm 65^0$	Triaxial Braid	Glass/epoxy
E	1	$\pm 75^0$	Triaxial Braid	Kevlar/epoxy
F	1	$\pm 75^0$	Triaxial Braid	Glass/epoxy
G	2	$\pm 65^0$	Triaxial Braid with Bonding Film and Steel Foil	Kevlar/epoxy
H	2	$\pm 65^0$	Triaxial Braid with Bonding Film and Steel Foil	Glass/epoxy
I	5	0^0	Unidirectional	Carbon/epoxy
J	9	-	Sandwich	2-Ply $\pm 65^0$ Triaxial Braid Kevlar/epoxy 5-Ply 0^0 Unidirectional Carbon/epoxy 2-Ply $\pm 65^0$ Triaxial Braid Kevlar/epoxy
K	-	-	Material J plus Bonding Film, 90^0 Steel Foil and Rubber Inhibitor on one side	-
L	-	-	Material J plus Bonding Film, and 90^0 Steel Foil on one side	-

TABLE 4 Test Matrix for Candidate Materials.

Material	Tensile Test (Room Temperature)	Tensile Test (Elevated Temperature Conditioned at 560^{0}F for One Second)	Slow Cook-Off Test	Fast Cook-Off Test
A	X	X		
B	X	X		
C	X	X	X	X
D	X	X	X	X
E	X	X		
F	X	X		
G	X	X	X	X
H	X	X	X	X
I	X	X	X	X
J	X	X	X	X
K	X	X		
L			X	X

X Indicates test performed.

TABLE 5 Summary of Ultimate Tensile Strengths of Material C for Width Effects Determination.

Nominal Width (in)	Tensile Strength		
	Average (psi)	Standard Deviation,s (psi)[b]	Coefficient of Variation, v[c]
1.00	11,026 (3)[a]	3469	31.5
1.25	13,395 (3)	538	4.0
2.00	14,460 (3)	908	6.3
3.00	13,826 (3)	329	2.4

a Numbers in parentheses indicate number of specimens tested.

b Standard deviation is defined $s = \sqrt{\frac{\Sigma(X_i - \overline{X})^2}{(number\ of\ samples - 1)}}$ where X_i is the value obtained for individual specimens and $\overline{X}$ is the average tensile strength.

c Coefficient of variation is defined v=100•s/(average tensile strength).

TABLE 6 Summary of Comparisons Made Between Material Systems.

	Braid Angle Effects		
Comparison Number	Comparisons Made		Materials Involved
1	Kevlar/epoxy single-ply	$\pm55^0$ vs $\pm65^0$ $\pm55^0$ vs $\pm75^0$ $\pm65^0$ vs $\pm75^0$	A vs C A vs E C vs E
2	Glass/epoxy single-ply	$\pm55^0$ vs $\pm65^0$ $\pm55^0$ vs $\pm75^0$ $\pm65^0$ vs $\pm75^0$	B vs D B vs F D vs F
3	Kevlar/epoxy single-ply vs Glass/epoxy single-ply	$\pm55^0$ vs $\pm55^0$	A vs B
4	Kevlar/epoxy single-ply vs Glass/epoxy single-ply	$\pm65^0$ vs $\pm65^0$	C vs D
5	Kevlar/epoxy single-ply vs Glass/epoxy single-ply	$\pm75^0$ vs $\pm75^0$	E vs F
	Dual-Ply Effects		
Comparison Number	Comparisons Made		Materials Involved
6	Kevlar/epoxy single-ply vs Kevlar/epoxy dual-ply	$\pm65^0$ vs $\pm65^0$	C vs G
7	Glass/epoxy single-ply vs Glass/epoxy dual-ply	$\pm65^0$ vs $\pm65^0$	D vs H
8	Kevlar/epoxy dual-ply vs Glass/epoxy dual-ply	$\pm65^0$ vs $\pm65^0$	G vs H
	Multi-Ply Effects		
Comparison Number	Comparisons Made		Materials Involved
9	Unidirectional carbon and Kevlar/epoxy dual-ply vs Kevlar-carbon-Kevlar/epoxy sandwich	-	G, I and J
10	Unidirectional carbon and Kevlar/epoxy dual-ply vs Kevlar-carbon-Kevlar/epoxy sandwich with Foil, Film and Inhibitor	-	G, I and K

TABLE 7 Summary of Comparisons Used for Tensile Strength and Tensile Modulus Data.

	Material Systems of Interest											
Baseline Materials	A	B	C	D	E	F	G	H	I	J	K	Baseline Materials
A		3[a]	1		1							A
B				2		2						B
C				4	1		6					C
D						2		7				D
E						5						E
F												F
G								8		9	10	G
H												H
I										9	10	I
J												J
K												K

a Numbers refer to "Comparison Number" in TABLE 6.

TABLE 8 Summary of Averaged Tensile Strength and Tensile Modulus of Materials A through K Tested at Room Temperature and Humidity.

Material	Tensile Strength			Tensile Modulus		
	Average (psi)	Standard Deviation, s[b] (psi)	Coefficient of Variation, v[c]	Average (ksi)	Standard Deviation, s (ksi)	Coefficient of Variation, v
A	15,674 (3)[a]	1,430	9.1	774.8 (3)	39.6	5.1
B	28,289 (4)	3,315	11.7	882.8 (4)	65.3	7.4
C	13,029 (3)	2,400	18.4	591.4 (3)	42.9	7.3
D	13,998 (3)	1,564	11.2	836.3 (2)	-	-
E	6,374 (4)	237	3.7	349.1 (3)	7.1	2.0
F	11,737 (5)	1,278	10.9	633.6 (3)	42.9	6.8
G	14,041 (3)	729	5.2	637.1 (3)	35.5	5.6
H	28,425 (3)	3,071	10.8	1,053 (2)	-	-
I	215,382 (3)	5,552	2.6	8,720 (3)	72	0.8
J	55,394 (3)	2,384	4.3	2,300 (2)	-	-
K	-	-	-	1,800 (3)	57	3.2

a Numbers in parentheses indicate number of specimens tested.

b Standard deviation is defined $s = \sqrt{\frac{\Sigma(X_i - \overline{X})^2}{(number\ of\ samples - 1)}}$ where X_i is the value obtained for individual specimens and $\overline{X}$ is the average tensile strength.

c Coefficient of variation is defined as v=100•s/(average tensile strength).

- Indicates data not obtained.

TABLE 9 Percent Differences of Ultimate Tensile Strength Between Baseline Materials (Vertical Axis) and Material Systems of Interest (Horizontal Axis), Tested at Room Temperature and Humidity.

	Material Systems of Interest											
Baseline Materials	A	B	C	D	E	F	G	H	I	J	K	Baseline Materials
A		+80[a]	-17		-59							A
B				-51		-59						B
C				+7	-51		+8					C
D						-16		+103				D
E						+84						E
F												F
G								+102		+295	-	G
H												H
I										-74	-	I
J												J
K												K

a Percentages rounded-off to nearest integer.

- Indicates data not obtained.

TABLE 10 Percent Differences of Tensile Modulus Between Baseline Materials (Vertical Axis) and Material Systems of Interest (Horizontal Axis), Tested at Room Temperature and Humidity.

	Material Systems of Interest											
Baseline Materials	A	B	C	D	E	F	G	H	I	J	K	Baseline Materials
A		+14[a]	-24		-55							A
B				-5		-28						B
C				+41	-41		+8					C
D						-24		+26				D
E						+81						E
F												F
G								+65		+261	+183	G
H												H
I										-74	-79	I
J												J
K												K

a Percentages rounded-off to nearest integer.

TABLE 11 Properties of S-2 Glass and Kevlar Fibers.

Fiber Material	Tensile Strength (ksi)	Tensile Modulus (Msi)	Density (lb/in^3)	Ref.
S-2 Glass	665	12.4	0.090	[46]
Kevlar 49	525	18	0.052	[47]
Kevlar 149	500	25	0.053	[47]

TABLE 12 Summary of Averaged Tensile Strength and Tensile Modulus of Materials A through K Exposed to a 560°F Environment for One Second and Tested at Room Temperature and Humidity.

Material	Tensile Strength			Tensile Modulus		
	Average (psi)	Standard Deviation, s[b] (psi)	Coefficient of Variation, v[c]	Average (ksi)	Standard Deviation, s (ksi)	Coefficient of Variation, v
A	18,055 (4)[a]	1,255	7.0	837.3 (3)	46.1	5.5
B	25,931 (4)	777	3.0	803.6 (4)	100.1	12.5
C	11,653 (3)	1,314	11.3	522.3 (3)	83.9	16.1
D	14,845 (3)	2,741	18.5	765.5 (3)	84.4	11.0
E	6,529 (5)	832	12.7	284.5 (3)	37.4	13.1
F	11,748 (4)	1,733	14.8	723.7 (2)	-	-
G	14,623 (3)	970	6.6	596.0 (3)	25.1	4.2
H	30,707 (3)	1,404	4.6	1,067 (3)	23	2.1
I	216,080 (3)	4,157	1.9	8,700 (3)	361	4.1
J	53,341 (3)	766	1.4	2,310 (3)	116	5.0
K	-	-	-	1,680 (3)	25	1.5

a Numbers in parentheses indicate number of specimens tested.

b Standard deviation is defined $s = \sqrt{\frac{\sum(X_i - \overline{X})^2}{(number\ of\ samples - 1)}}$ where X_i is the value obtained for individual specimens and $\overline{X}$ is the average tensile strength.

c Coefficient of variation is defined as v=100•s/(average tensile strength).

- Indicates data not obtained.

TABLE 13 Percent Differences of Ultimate Tensile Strength Between Baseline Materials (Vertical Axis) and Material Systems of Interest (Horizontal Axis), Exposed to a 560^{0}F Environment for One Second and Tested at Room Temperature and Humidity.

	Material Systems of Interest											
Baseline Materials	A	B	C	D	E	F	G	H	I	J	K	Baseline Materials
A		+44[a]	-35		-64							A
B				-43		-55						B
C				+27	-44		+25					C
D						-21		+107				D
E						+80						E
F												F
G								+110		+265	-	G
H												H
I										-75	-	I
J												J
K												K

a Percentages rounded-off to nearest integer.

- Indicates data not obtained.

TABLE 14 Percent Differences of Tensile Modulus Between Baseline Materials (Vertical Axis) and Material Systems of Interest (Horizontal Axis), Exposed to a 560°F Environment for One Second and Tested at Room Temperature and Humidity.

	Material Systems of Interest											
Baseline Materials	A	B	C	D	E	F	G	H	I	J	K	Baseline Materials
A		-4[a]	-38		-66							A
B				-5		-10						B
C				+47	-46		+14					C
D						-5		+39				D
E						+154						E
F												F
G								+79		+288	+182	G
H												H
I										-73	-81	I
J												J
K												K

a Percentages rounded-off to nearest integer.

TABLE 15 Comparison of Ultimate Tensile Strength and Tensile Modulus for Room Temperature and Elevated Temperature Conditioned Materials.

	Ultimate Tensile Strength (psi)			Tensile Modulus (ksi)		
Material	R. T.[a]	E. T.[b]	Percent Change[c]	R. T.	E. T.	Percent Change
A	15,674	18,055	+15	774.8	837.3	+8
B	28,289	25,931	-8	882.8	803.6	-9
C	13,029	11,653	-11	591.4	522.3	-12
D	13,998	14,845	+6	836.3	765.5	-8
E	6,374	6,529	+2	349.1	284.5	-19
F	11,737	11,745	+0.1	633.6	723.7	+14
G	14,041	14,623	+4	637.1	596.0	-6
H	28,425	30,707	+8	1,053	1,067	+1
I	215,382	216,080	+0.3	8,720	8,700	-0.2
J	55,394	53,341	-4	2,300	2,310	+0.4
K	-	-	-	1,800	1,680	-7

a R. T. denotes specimens tested at room temperature and humidity.

b E. T. denotes specimens exposed to a 560^{0}F environment for one second and tested at room temperature and humidity.

c Percent change = (E.T. - R.T.)/R.T.

- Indicates data not obtained.

TABLE 16 Summary of Results of Slow Cook-Off Testing.

Material	Qualitative Observations after Exposure to Testing Temperatures for One Hour		
	237.50^{0}F	356.25^{0}F	475.00^{0}F
C	- No visible effects (NVE).	- Mild discoloration to a shade of light brown. - Slight warpage of entire coupon.	- Gross discoloration to a shade of dark brown. - Much weaker in flexure than virgin specimens.
D	- Material was stiffer when flexed by hand.	- Mild discoloration to a shade of light brown. - Stiffer than 237^{0}F test and virgin material.	- Gross discoloration to a shade of dark brown. - Stiffest of all material D specimens.
G	- NVE	- Mild discoloration of epoxy and foil to shades of light brown. - Initial foil delamination evident.	- Gross discoloration to shade of dark brown. - Foil starting to turn rust-brown in color. - Slight foil delamination.
H	- NVE	- Moderate discoloration of epoxy to shade of light brown. - Spotty discoloration of foil to rust-brown color. - Foil showed no signs of delamination.	- Gross discoloration to shade of dark brown. - Spotty discoloration of foil to rust-brown color. - No signs of delamination of foil.

(Continued on next page)

TABLE 16 (Continued) Summary of Results of Slow Cook-Off Testing.

Material	Qualitative Observations after Exposure to Testing Temperatures for One Hour		
	237.50°F	356.25°F	475.00°F
I	- NVE	- Visible change of epoxy on surface of composite. - Moderately less stiff in flexure.	- Visible change of epoxy on surface of composite, although not much different than 356.25°F specimens. - Moderately less stiff in flexure. - Discoloration to an off-brown color.
J	- NVE - Retained heat longer than other materials.	- Very slight discoloration.	- Gross discoloration to shades of dark brown.
L	- NVE - Retained heat longer than other materials.	- Very slight discoloration on epoxy and foil to light brown colors.	- Gross dark discoloration of epoxy to dark brown. - Slight rust-brown stains evident on foil.

TABLE 17 Summary of Fast Cook-Off Testing Observations.

Material	Time from Start of Test (min)	Sequential Qualitative Observations at Indicated Time
C	<15 seconds	- Kevlar braid separating. - Specimen being consumed by flame very quickly. - Epoxy disintegrating. - Structural integrity lost. - END OF TEST.
D	1	- Fiberglass braid separating. - Epoxy disintegrating.
	2	- Flame pushing specimen over. - Folding of specimen evident.
	3	- Epoxy burning away. - Structure becoming "orange" hot. - Structural integrity lost. - END OF TEST.
G	<30 seconds	- Kevlar fibers on fire. - Braided fiber separating. - Foil bending back from specimen. - Kevlar delaminating from foil. - Structure folding away from flame. - Foil falling off back of specimen. - Structural integrity lost. - END OF TEST.
H	1	- Specimen deflecting flame.
	2	- Epoxy "bubbling" on surface of material. - Material burning at point of flame impingement.
	3	- Specimen swelling.
	4	- Material starting to shrink at sides, similar to necking. - Structure starting to melt. - Flame starting to push specimen over.
	5	- Specimen folding onto itself. - Structural integrity lost. - END OF TEST.

(Continued on next page)

TABLE 17 (Continued) Summary of Fast Cook-Off Testing Observations.

Material	Time from Start of Test (min)	Sequential Qualitative Observations at Indicated Time
I	1	- Carbon/epoxy beginning to warp. - Epoxy being consumed by flame. - Carbon fiber near edges starting to show.
	2	- Flame glowing through specimen. - Fibers being exposed in flame area. - Exposed fibers being consumed by flame.
	3	- Epoxy burning away, exposing carbon fibers. - Exposed fibers continuing to be consumed. - Cracking on backside of specimen observed.
	4	- No change in observations.
	5	- Specimen missing large pockets of epoxy. - Backside of specimen bulging outward. - Flame starting to push areas at flame impingement.
	6	- Flame penetrating through specimen. - Consumption of epoxy nearly complete. - Structural integrity lost. - END OF TEST.
J	1	- Localized swelling apparent. - Upper layer of epoxy disintegrating. - Flame making a hole in the epoxy. - Outer layer of Kevlar/epoxy delaminating and separating from structure.
	2	- Kevlar fibers delaminating on both sides of the specimen. - Carbon/epoxy maintaining its shape. - Carbon/epoxy warping about 0^0 fiber direction.
	3	- Flame glowing through specimen. - Kevlar completely consumed. - Carbon/epoxy beginning to "ripple".

(Continued on next page)

TABLE 17 (Continued) Summary of Fast Cook-Off Testing Observations.

Material	Time from Start of Test (min)	Sequential Qualitative Observations at Indicated Time
J	4	- No change in observations.
	5	- Epoxy starting to burn away. - Carbon fibers becoming exposed.
	6	- Carbon fibers being exposed and comsumed by flame. - Specimen thinning is apparent at point of flame impingement.
	7	- Tufts of carbon fibers showing. - Bulging on backside of specimen.
	8	- No change in observations.
	9	- Carbon fibers cracking away from surface.
	10	- Flame completely through the carbon. - Structural integrity lost. - END OF TEST.
L	1	- Resin starting to disintegrate. - Kevlar layer bulging toward flame. - First layer starting to delaminate and separate from structure.
	2	- Kevlar and epoxy burning. - Carbon/epoxy becoming visible.
	3	- Kevlar and foil delaminating on backside of carbon material. - Foil bending back from carbon. - Kevlar fibers falling back after total delamination from structure.
	4	- Epoxy burning away.
	5	- Kevlar holding up better in this material than in Material J.
	6	- No change in observations.

(Continued on next page)

TABLE 17 (Continued) Summary of Fast Cook-Off Testing Observations.

Material	Time from Start of Test (min)	Sequential Qualitative Observations at Indicated Time
L	7	- Flame cutting through upper layer of Kevlar.
	8	- Foil on back not contributing to structural integrity. - Carbon starting to warp around 0^0 fiber direction.
	9	- Foil falling off back of material.
	10	- Outermost layer of Kevlar/epoxy falling off. - Flame impinging directly on carbon/epoxy.
	11	- Carbon/epoxy bulging slightly away from flame.
	12	- No change in observations.
	13	- Tufts of fiber being exposed and consumed by flame.
	14	- More carbon fibers being exposed and consumed.
	15	- Time limit reached. - Structural integrity reduced but intact. - END OF TEST.

TABLE 18 Summary of Comparisons of Relative Performance of Materials A through K.*

	Room Temperature		Elevated Temperature Conditioned at 560°F for One Second		Resistance During Cook-Off Tests	
Material	Tensile Strength	Tensile Modulus	Tensile Strength	Tensile Modulus	Slow Cook-Off	Fast Cook-Off
A	Moderate	Good	Good	Good	-	-
B	Good	Good	Good	Good	-	-
C	Moderate	Moderate	Moderate	Moderate	Moderate	Poor
D	Good	Good	Moderate	Good	Moderate	Moderate
E	Moderate	Moderate	Moderate	Moderate	-	-
F	Good	Moderate	Good	Moderate	-	-
G	Moderate	Moderate	Moderate	Moderate	Moderate	Poor
H	Good	Good	Good	Good	Moderate	Moderate
I	Excellent	Excellent	Excellent	Excellent	Good	Good
J	Excellent	Excellent	Excellent	Excellent	Good	Good
K	-	Good	-	Good	-	-
L	-	-	-	-	Good	Excellent

* The relative descriptions, "Excellent", "Good", "Moderate", and "Poor" are intended for comparisons between materials considered in this research, and should not be regarded as descriptions for comparisons with other materials.

\- Indicates data not obtained.

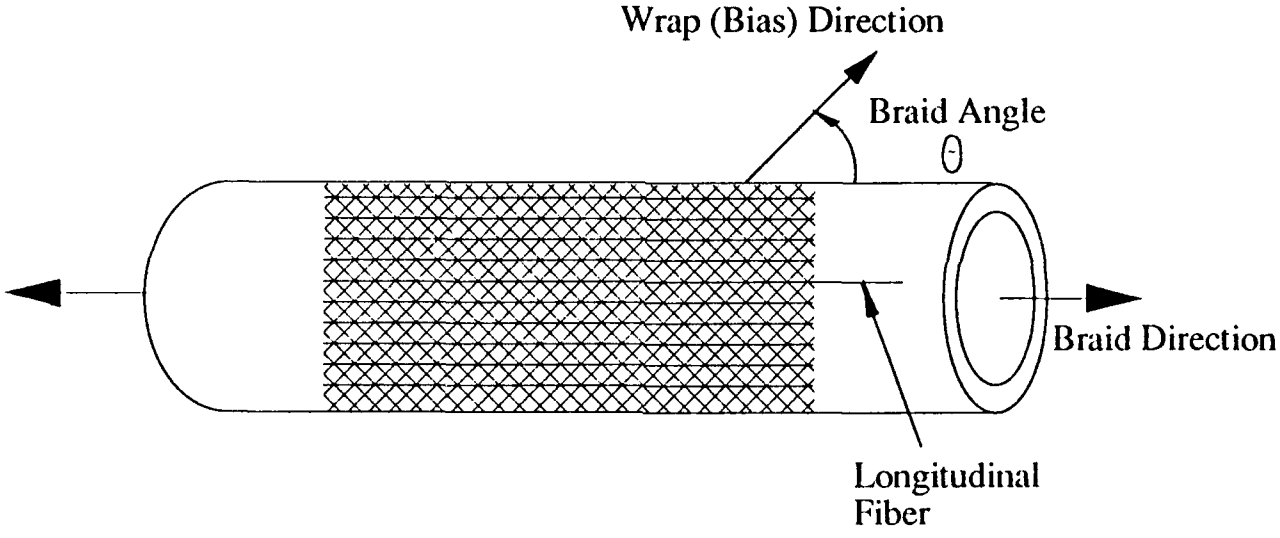


Fig. 1 Definition of braid angle.

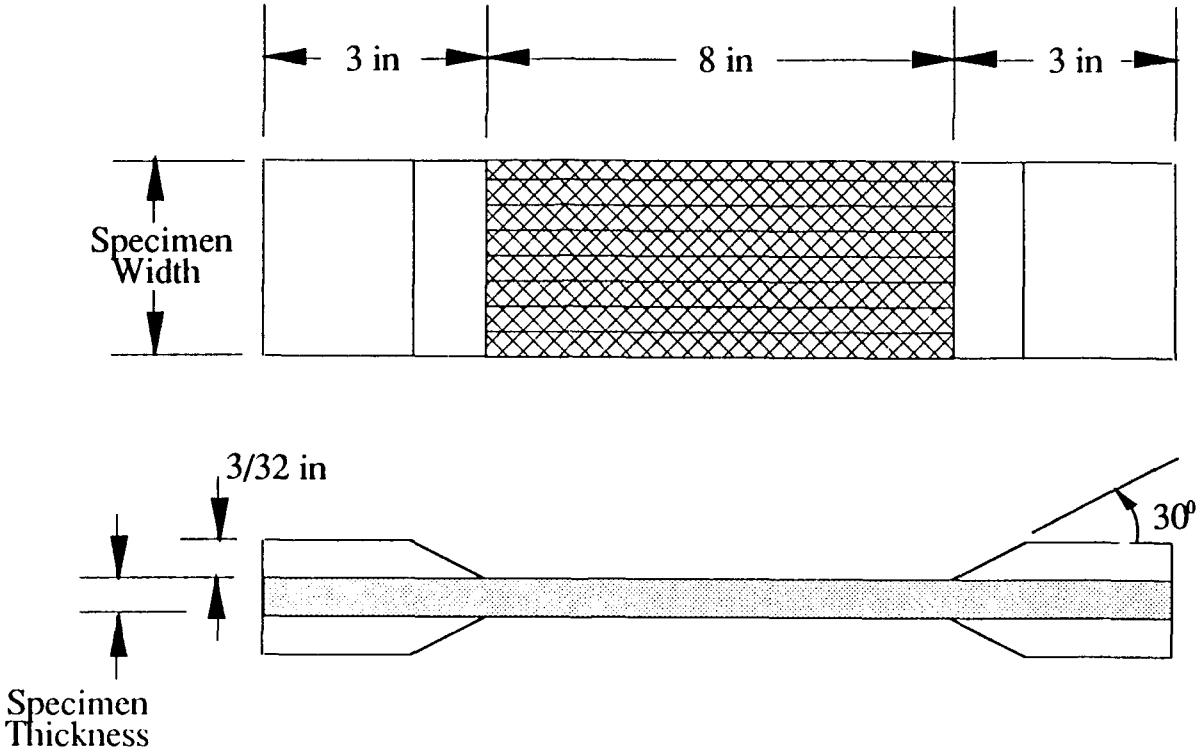
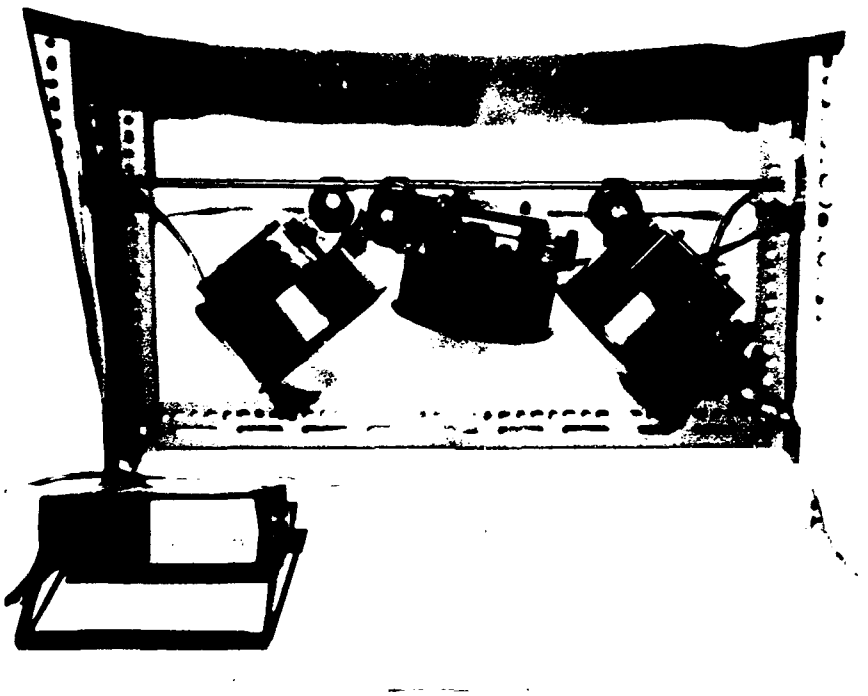


Fig. 2 Schematic of tensile test specimen, including tapered tabs.



6 in

Fig. 3 Photograph of environmental chamber used for elevated temperature conditioning, showing relative position of spotlights, conditioning area with sample in place, thermocouple wire, and digital thermometer readout.

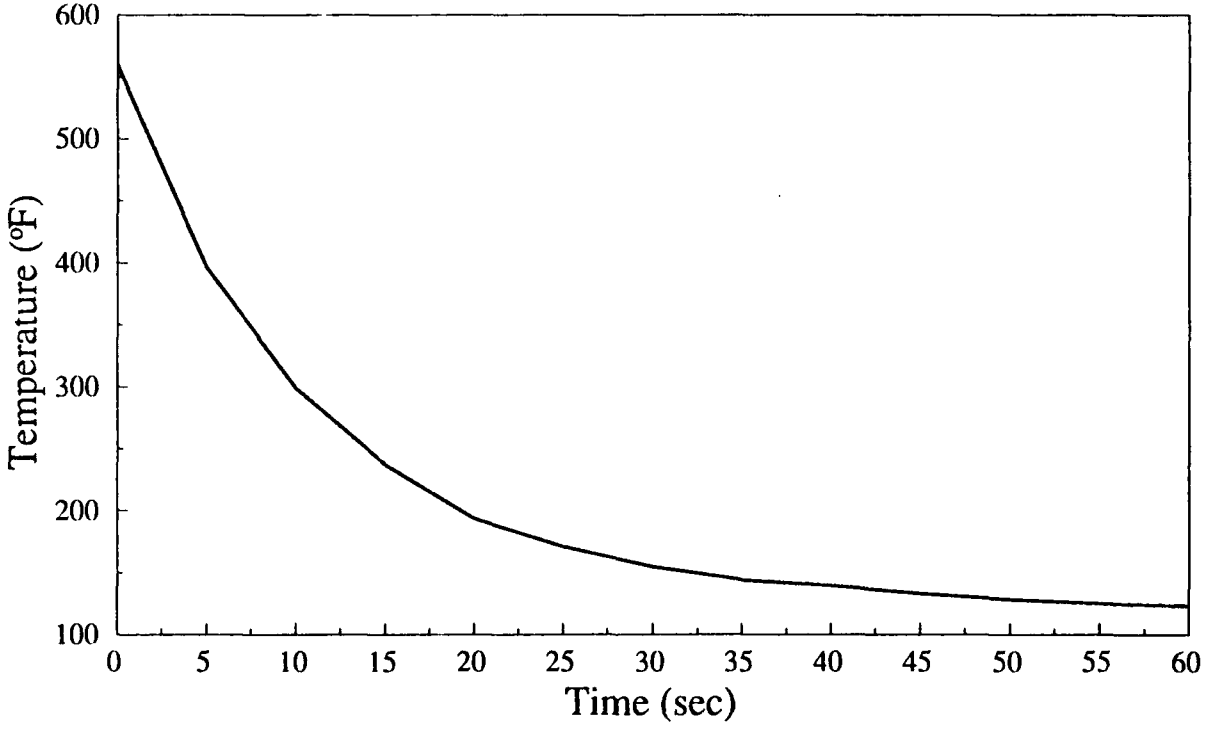


Fig. 4 Temperature decay versus time in elevated temperature environmental chamber.

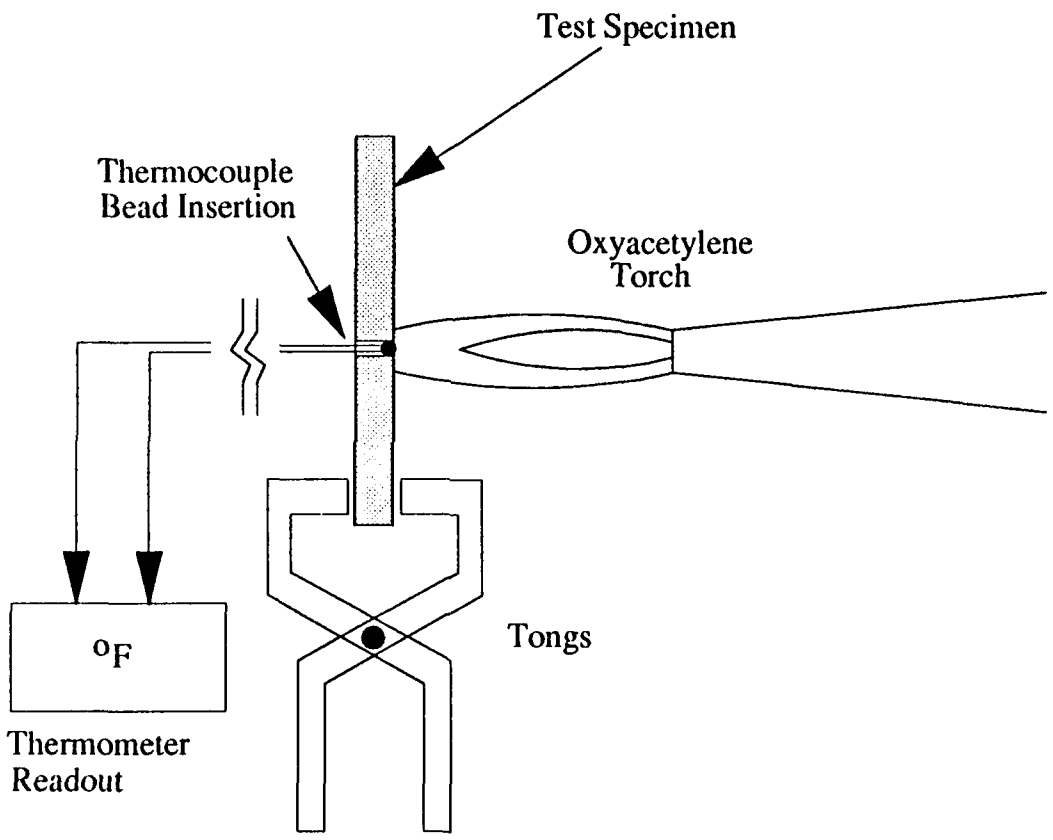


Fig. 5 Schematic of fast cook-off set-up showing relative positions of flame, specimen and thermocouple bead.

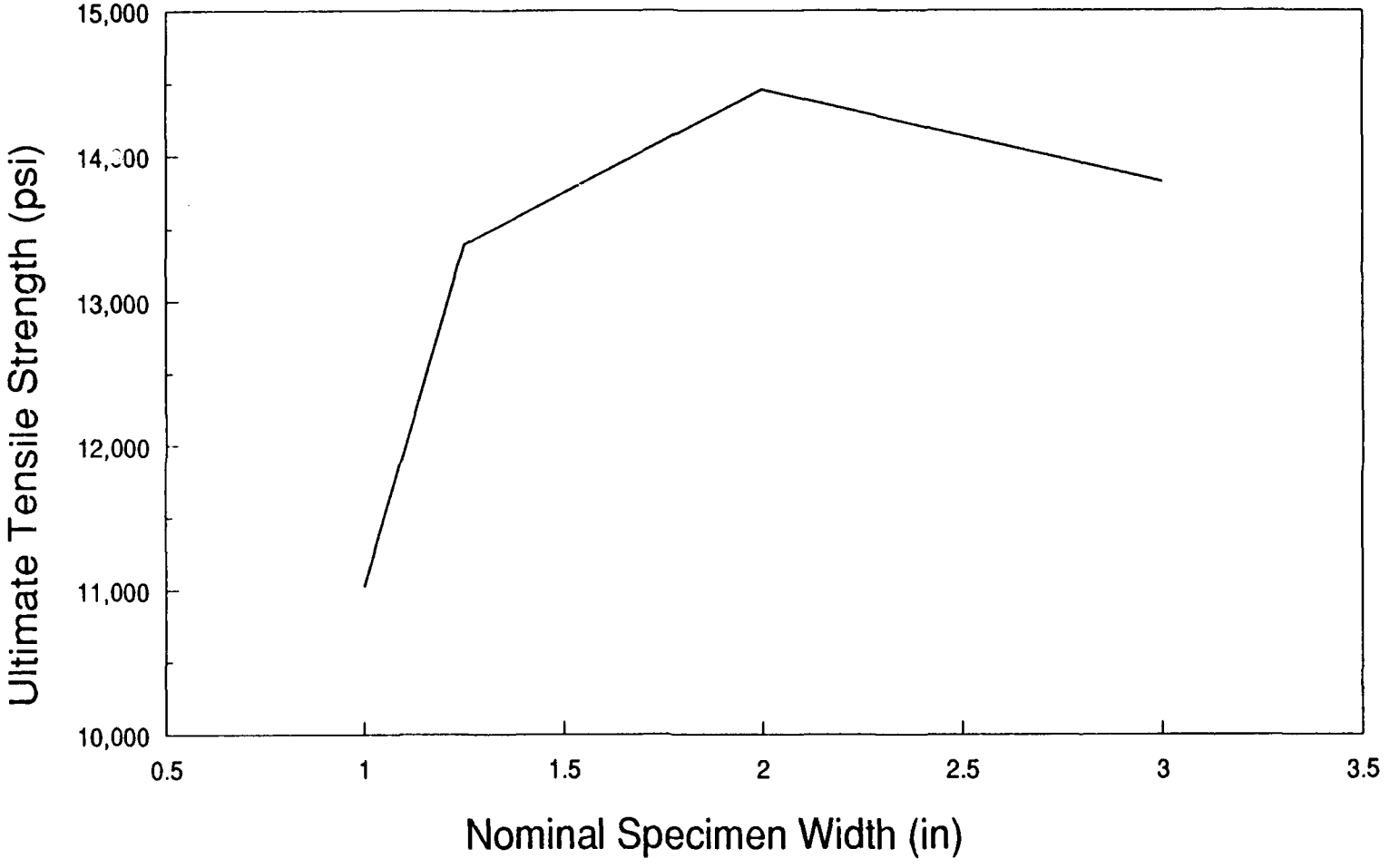


Fig. 6 Ultimate tensile strength versus nominal specimen width of material C for width effects determination.

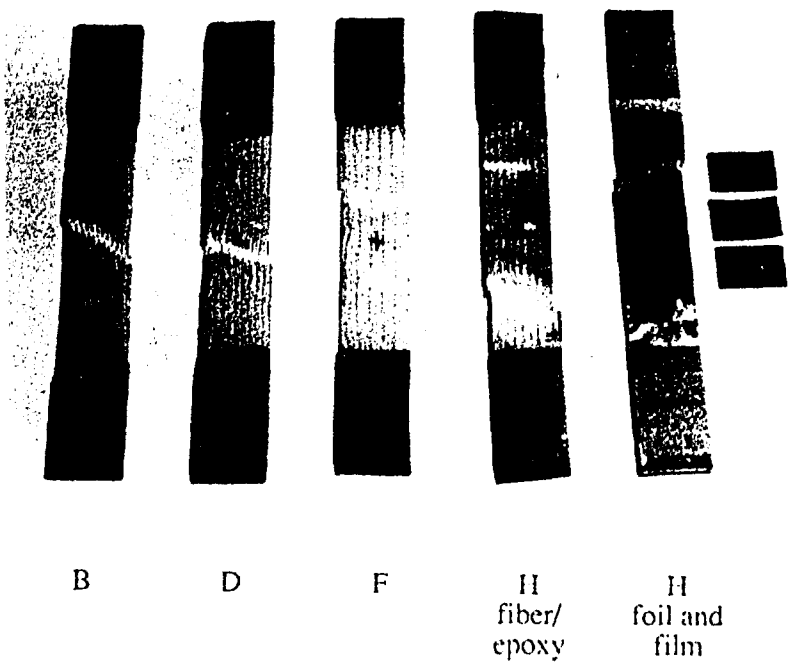
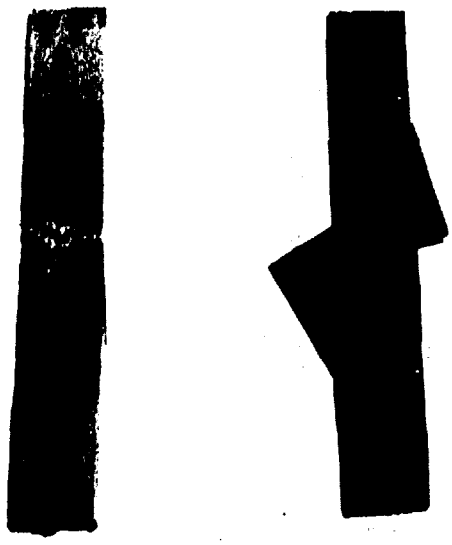


Fig. 7 Photograph of typical tensile ruptured specimens (room temperature or elevated temperature conditioned at 560°F for one second) of materials B, D, F, H (fiber/epoxy side), H (foil and film side), showing displaced foil strips from the foil and film side of material H.

Fig. 8 Photograph of typical tensile ruptured specimens (room temperature or elevated temperature conditioned at 560°F for one second) of materials A, C, E, G (fiber/epoxy side), G (foil and film side), showing displaced foil strips from the foil and film side of material G.

Fig. 9 Photograph of typical tensile ruptured specimens (room temperature or elevated temperature conditioned at 560°F for one second) of materials H and G, (fiber/epoxy side), and H and G (foil and film side), showing displaced foil strips from the foil and film side of materials H and G.



J K

Fig. 10 Photograph of typical tensile ruptured specimens (room temperature or elevated temperature conditioned at 560°F for one second) of materials J and K, showing delamination of the rubber inhibitor on material K.

Fig. 11 Photograph of typical tensile ruptured specimen (room temperature or elevated temperature conditioned at 560^{0}F for one second) of material I.

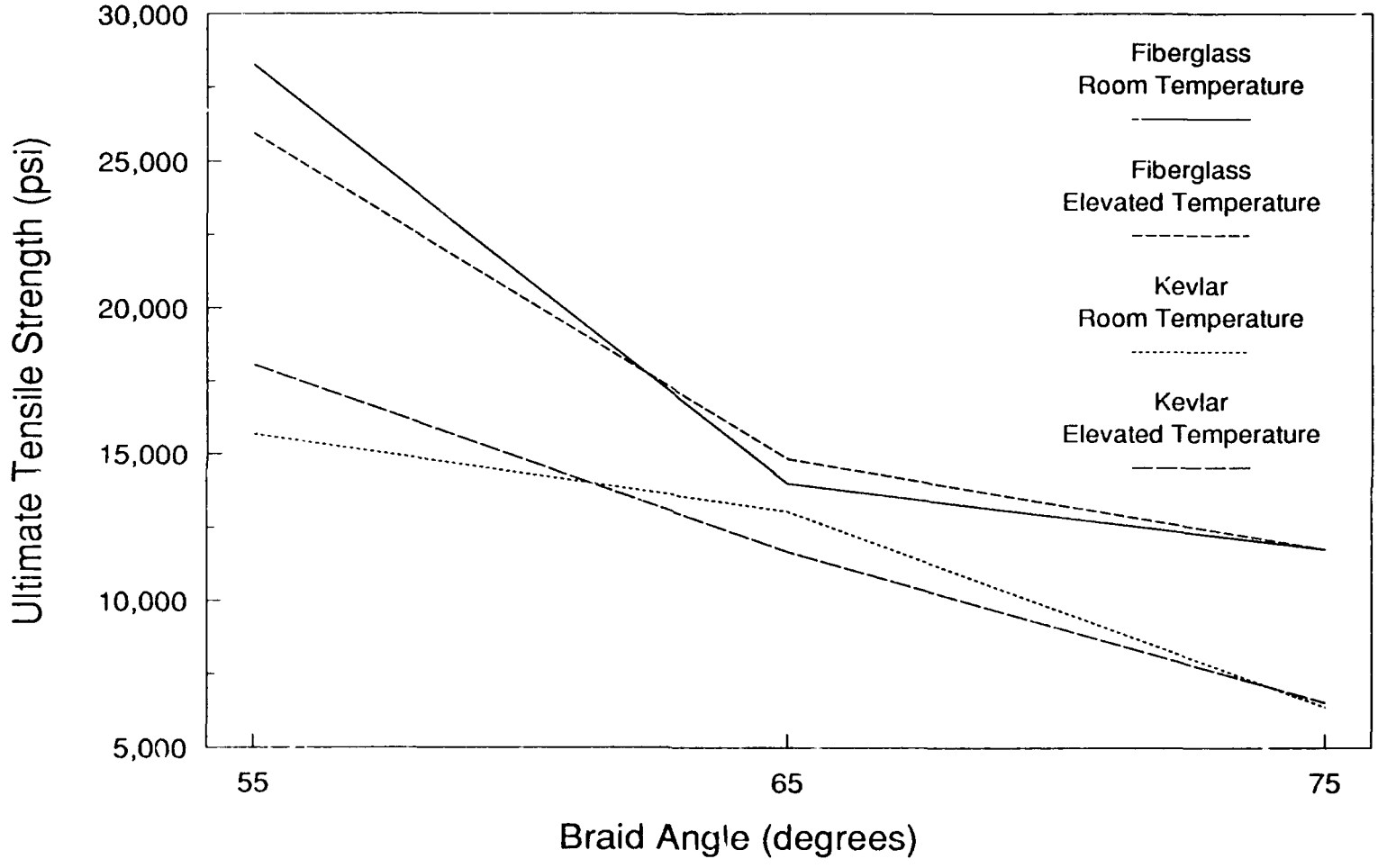


Fig. 12 Ultimate tensile strength versus braid angle for single ply laminates at room temperature and after elevated temperature conditioning at 560^0F for one second.

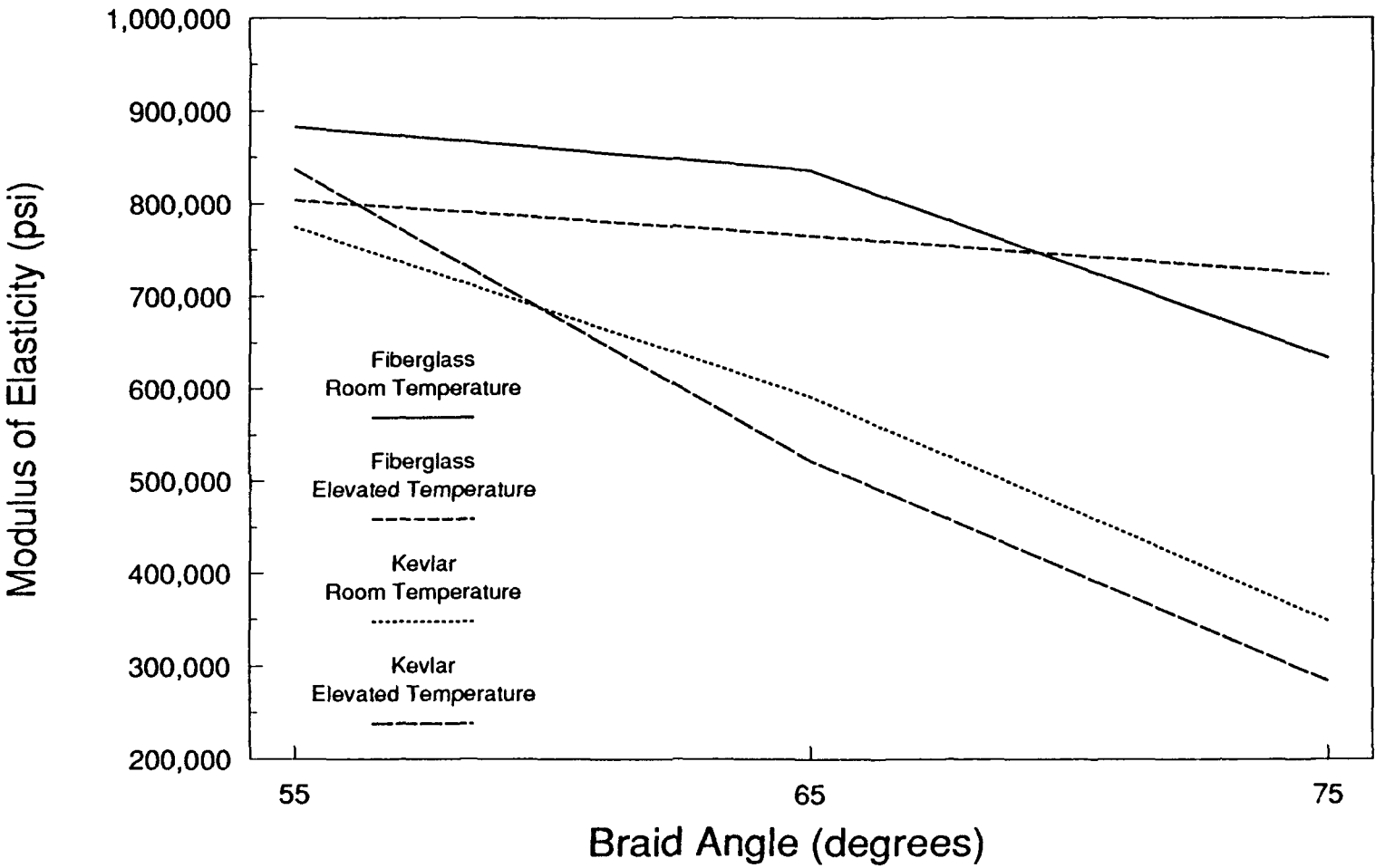


Fig. 13 Modulus of elasticity versus braid angle for single ply laminates at room temperature and after elevated temperature conditioning at 560°F for one second.

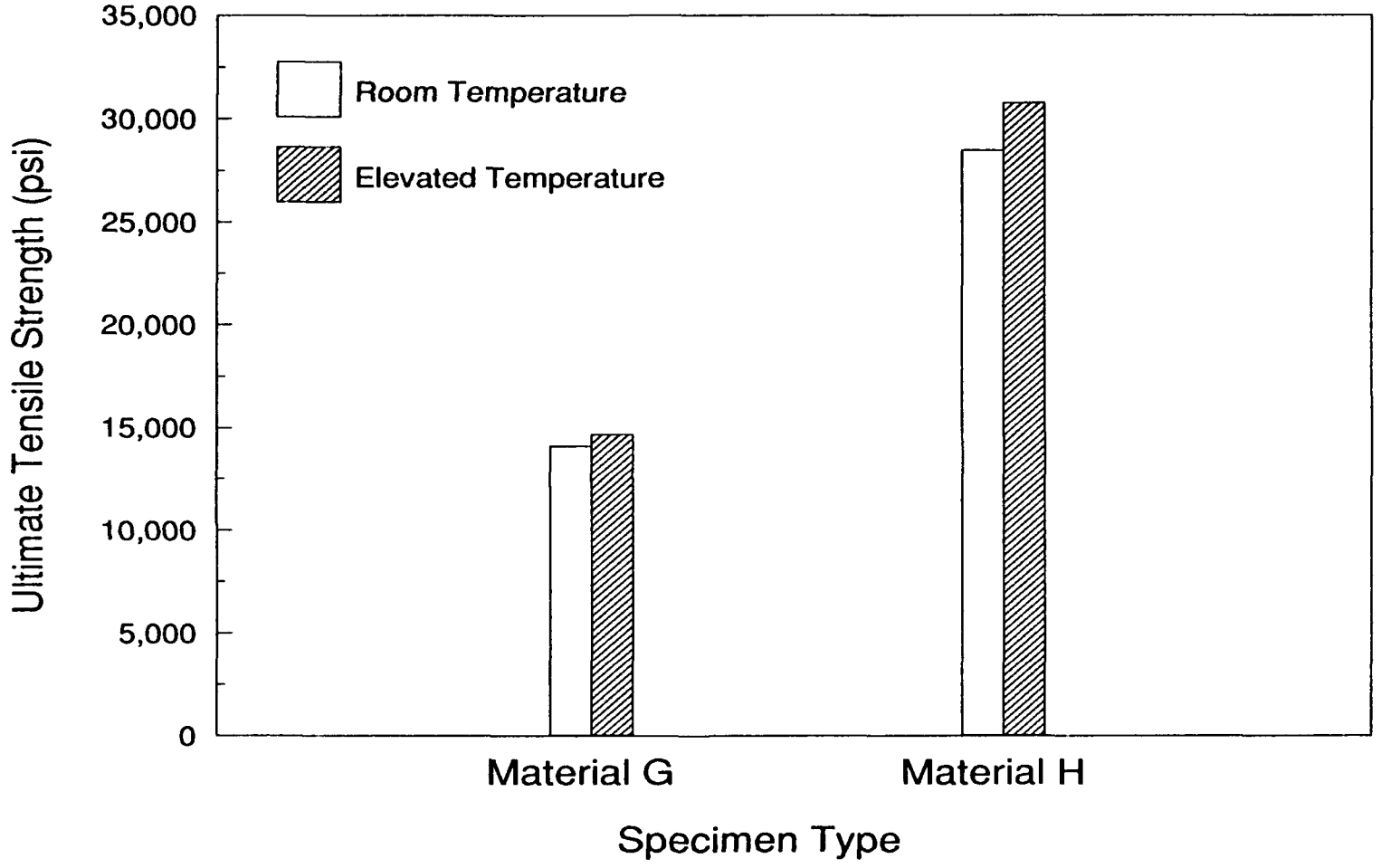


Fig. 14 Ultimate tensile strength versus specimen type for dual-ply laminates at room temperature and after elevated temperature conditioning at 560^{0}F for one second.

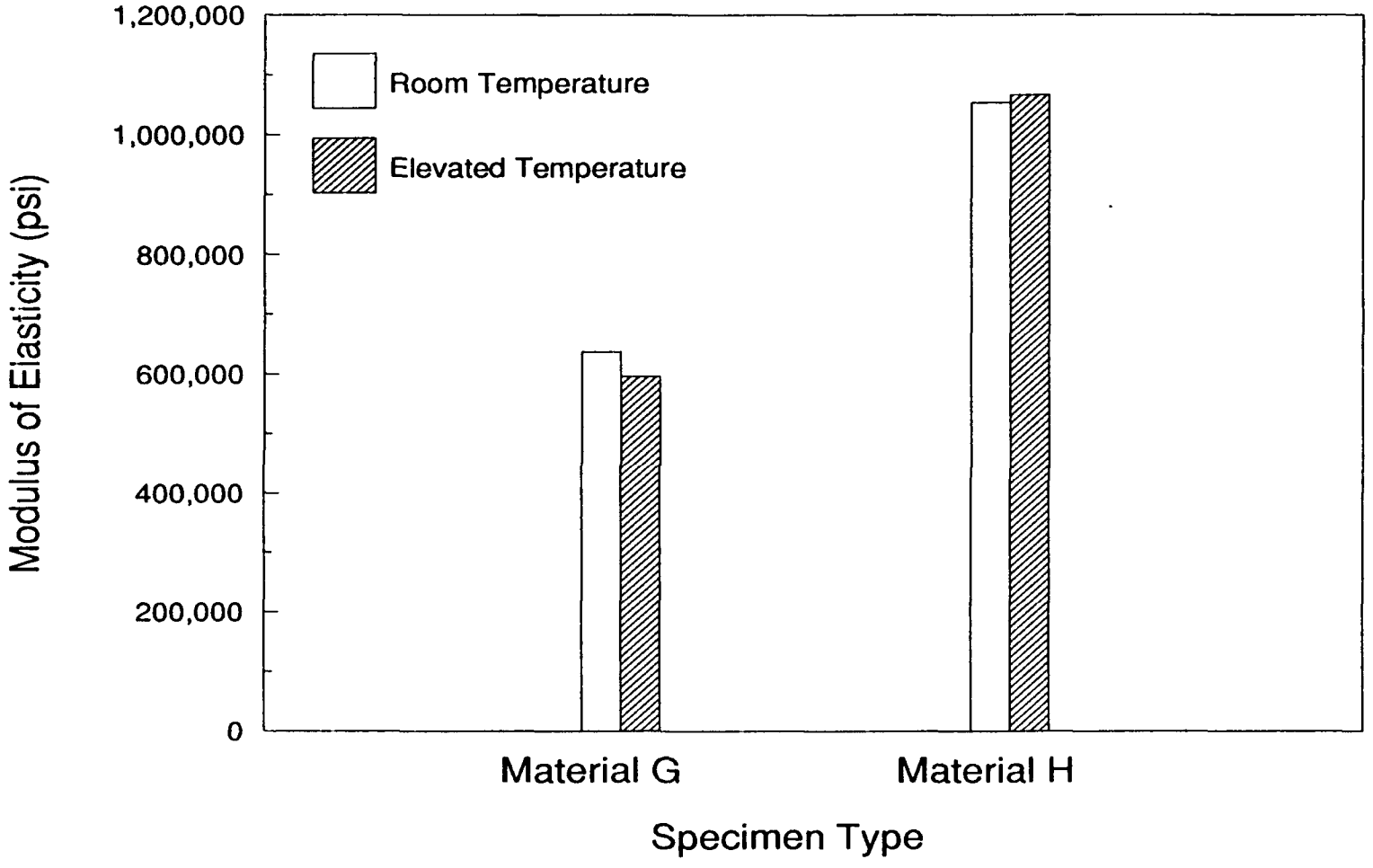


Fig. 15 Modulus of elasticity versus specimen type for dual-ply laminates at room temperature and after elevated temperature conditioning at 560°F for one second.

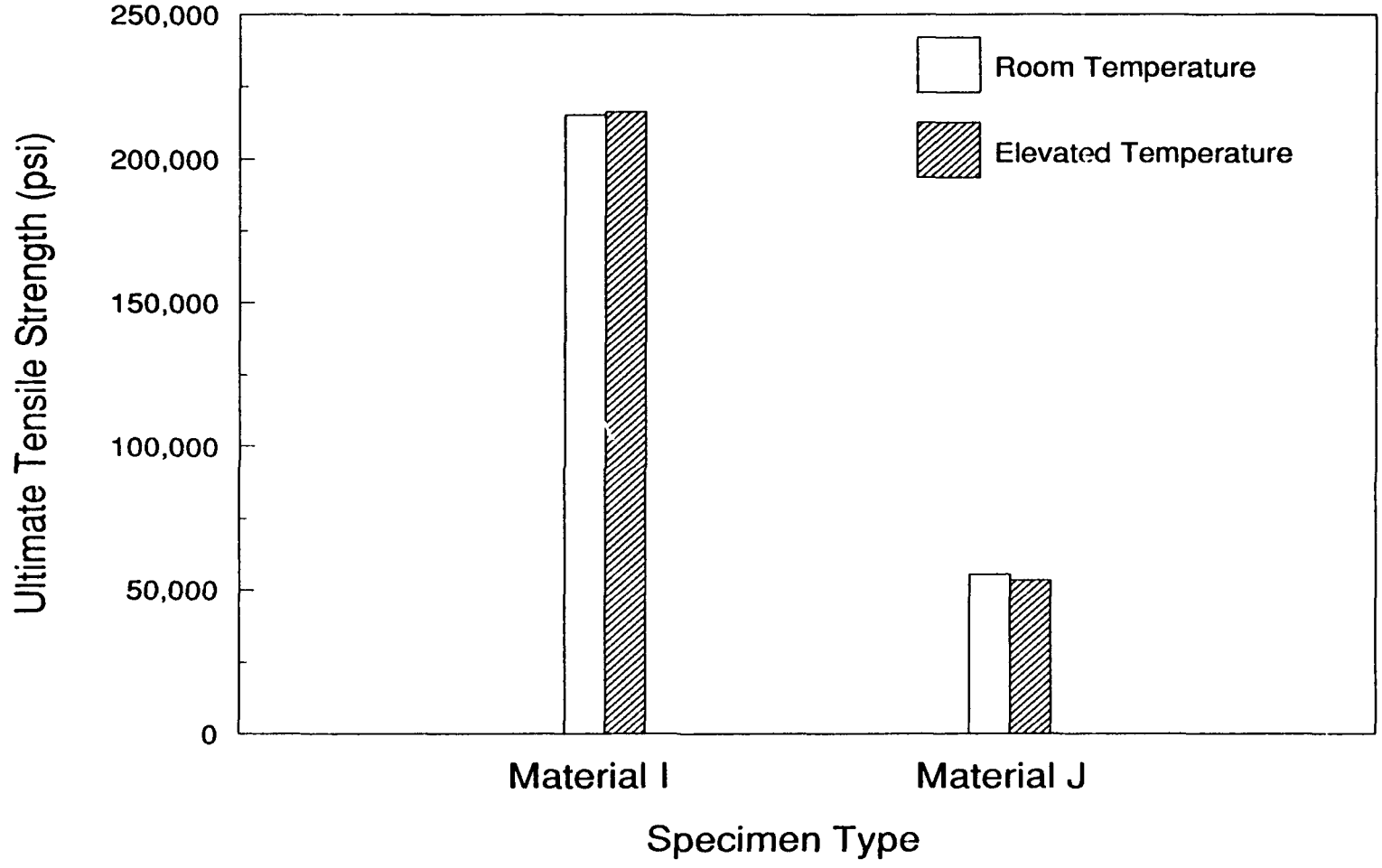


Fig. 16 Ultimate tensile strength versus specimen type for multi-ply laminates at room temperature and after elevated temperature conditioning at 560^{0}F for one second.

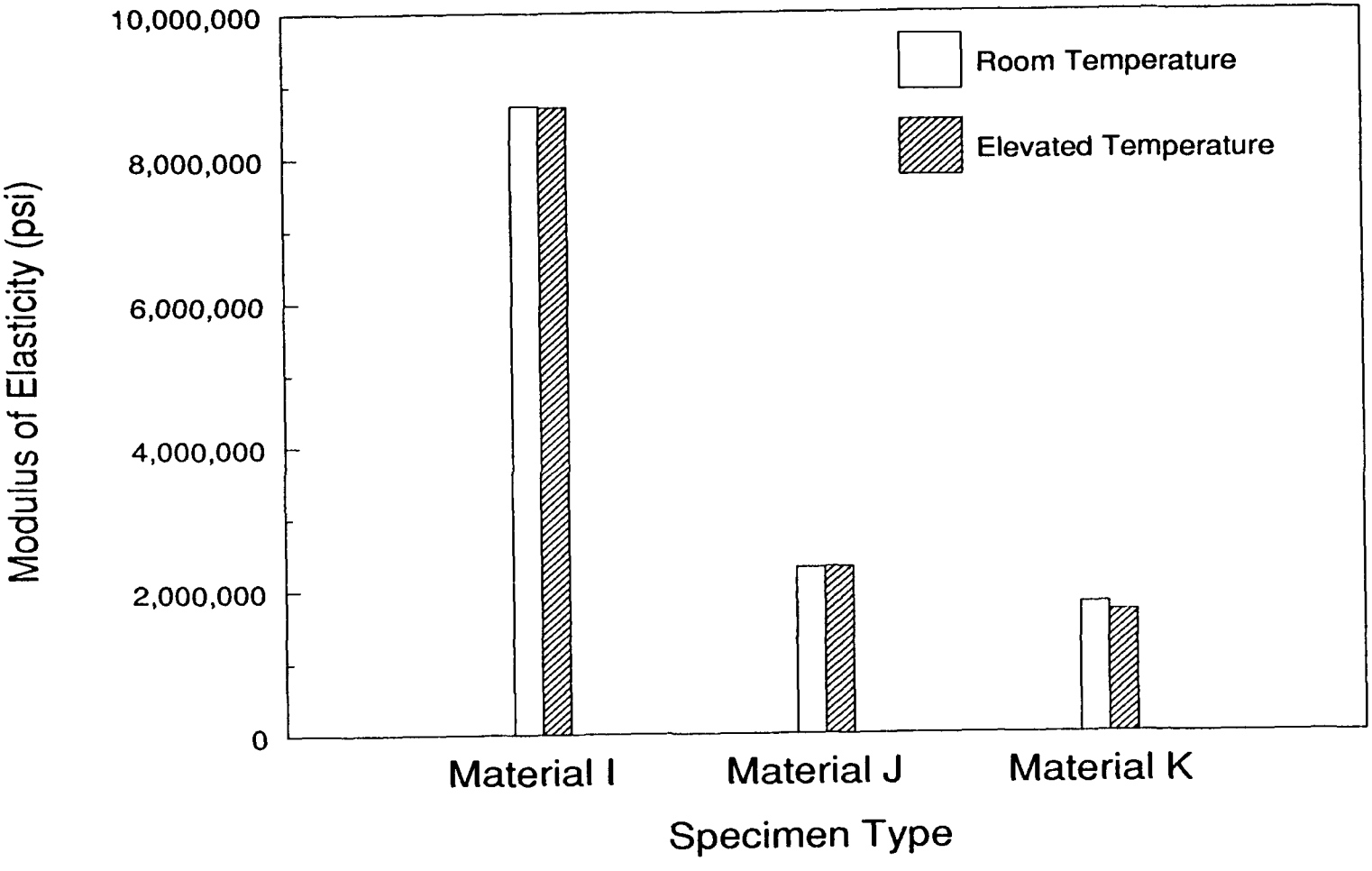


Fig. 17 Modulus of elasticity versus specimen type for carbon fiber reinforced epoxy and multi-ply laminates at room temperature and after elevated temperature conditioning at 560^{0}F for one second.

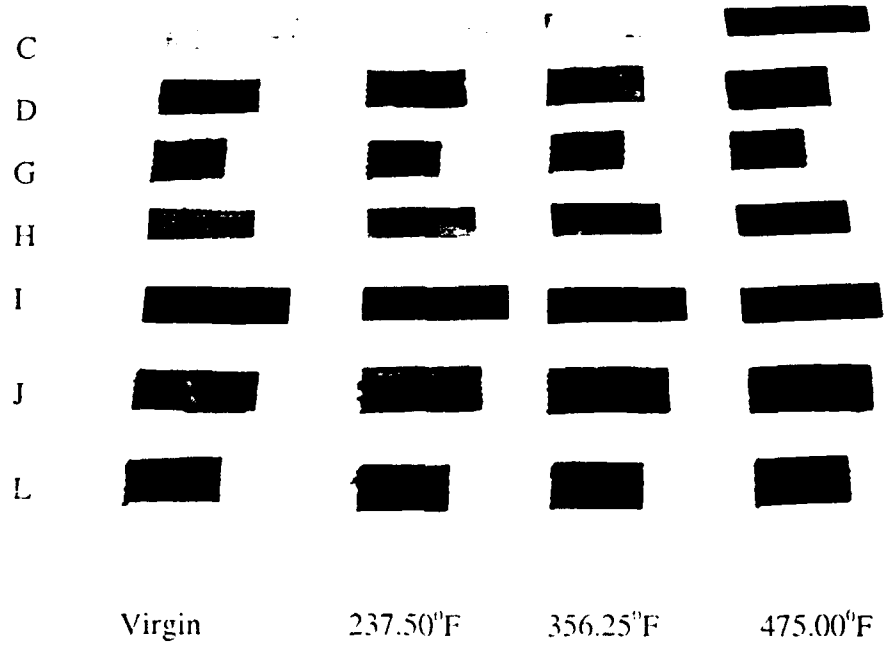


Fig. 18 Photograph showing virgin specimens and slow cook-off test specimens.

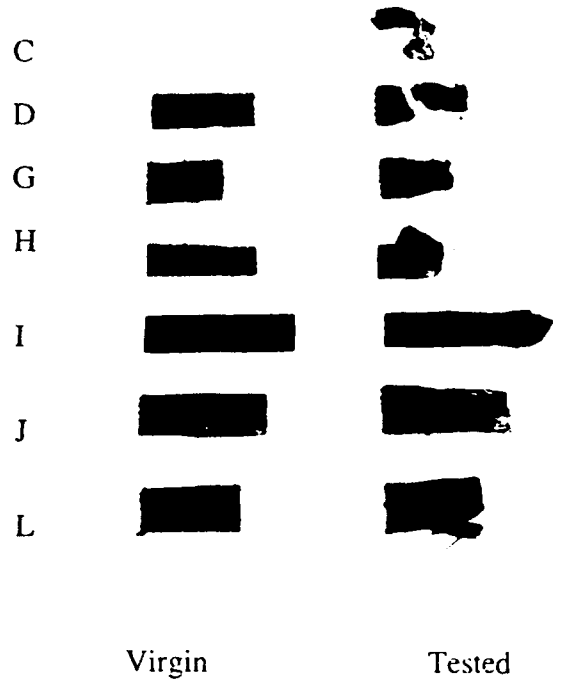


Fig. 19 Photograph showing virgin specimens and fast cook-off test specimens.

APPENDIX A: TEST SPECIMEN PROPERTIES AND FABRICATION PROCEDURE

Physical Properties

All candidate specimens are manufactured by U.S. Composites Corporation, Troy, New York. Physical property information is supplied by the manufacturer and is shown in Table A1. Theoretical values for fiber volume fraction are supplied by U.S. Composites [A1], and are summarized in Table A2. Void content information is not available.

Specimen Design

The width effect determination and tensile test specimens are 14 inches long, with various thicknesses dependent on the material system. Width effect determination tensile test specimens vary from one inch to 3.25 inches wide. All other tensile test specimens are 2.0 inches wide. The tabbing material is 3/16-inch thick 3M Scotchply Type 1002 crossply E-glass continuous filament composite. Dexter HYSOL EA 934 is used to adhere the tabs to the specimens. The adhesive is a two-component epoxy that cures at room temperature to a shear strength of 3100 psi [A2].

Cook-off test specimens measure approximately 3 square inches. Actual dimensions of the specimens range from approximately 1 inch by 3 inches to approximately 1.5 inches by 2 inches. They are cut from panels as delivered by the manufacturer. No further conditioning or preparation is necessary prior to testing.

Tensile Test Specimen Fabrication Procedure

Panels are received from U.S. Composites in nominal widths of 4 to 12.5 inches and lengths of 28 to 31 inches. Using a diamond-blade table saw for glass/epoxy and carbon/epoxy panels, and a reversed band saw for Kevlar materials, the specimens are cut to lengths of 14 inches.

Scotchply Type 1002 crossply E-glass continuous filament composite tabs are used to protect the specimens from damage in the testing grips. Tabs are cut on a diamond-blade table saw to dimensions of 3 inches x W inches (where W is the width of individual panels). A 30 degree taper is cut onto the leading edge of the tab to reduce stress concentrations in the adhesive during testing.

The tabs are roughened with a file on the side that is to face the composite. Several scratches in both the normal and parallel directions are made in the tabs. The ends of the composite specimens are similarly roughened to increase contact area with the tabs. Methylene chloride ($MeCl_2$) is used to clean the tabs and specimens, thus removing any moisture and residue.

The adhesive, HYSOL EA 934, is prepared using 100 parts by weight of Part A and 33 parts by weight of Part B. The adhesive is then spread thinly onto the scratched side of the tabs. The tabs are then placed into position on the specimen and clamped into place. Enough pressure is applied such that excess adhesive is squeezed out. Curing of the adhesive takes place at room temperature (70^0F) for at least 24 hours.

The 14 inch panels, with tabs affixed, are cut to test widths on the same equipment used to make preliminary cuts. The outside 0.5 inch of each panel is cut away and discarded to eliminate irregularities in the specimens.

References

A1. Conversation with George Earle, U.S. Composites, Troy, New York, 22 January 1990.

A2. "EA 934NA", Dexter Hysol Aerospace and Industrial Products Division. Pittsburg, CA, March 1987.

TABLE A1 Physical Property Information for Candidate Materials.

Item	Description
Braid	All braided specimens are two-dimensional, triaxially configured.
Kevlar Fiber	Wrap Fiber: 1420 denier Kevlar 49, $\pm\theta^0$ Warp Fiber: 1140 denier Kevlar 149, 0^0
Glass Fiber	Wrap Fiber: 1250 Y (1250 yards per pound) S-2 Glass, $\pm\theta^0$ Warp Fiber: 1250 Y S-2 Glass, 0^0
Carbon	Fortafil Carbon/epoxy pre-preg, 0^0
Epoxy	Dow Tactix 138
Catalyst	70/30 Blend of Dow H31/H41
Cure Cycle	60 minute ramp to 180^0F 60 minute soak at 180^0F 60 minute ramp to 300^0F 60 minute soak at 300^0F
Bonding Film	2-Plies of 3M Brand 583 Bonding Film
Foil	1-Ply, 0.002 inches thick stainless steel
Inhibitor	1-Ply, 0.050 inches thick EPDM rubber

TABLE A2 Theoretical Values of Total Fiber Volume Fraction for Candidate Materials.*

Material	Fiber Volume Fraction (percent)
A	59.0
B	48.0
C	57.0
D	47.0
E	60.4
F	51.0

Material	Fiber Volume Fraction (percent)
G	56.3
H	47.0
I	65.0
J	59.2
K	59.2
L	59.2

* The theoretical fiber volume fraction of dual-ply and multi-ply materials reported is the total fiber volume fraction for the composite.

APPENDIX B: TEST PROCEDURES AND EQUIPMENT

Width Effects and Tensile Testing

All width effect determination and tensile test specimens are tested on a Materials Testing System (MTS) Model 810. The MTS is rated to 100 Metric Tons, and calibrated to 100,000 pounds. MTS Series 641 non-aligning hydraulic grips hold the specimens in place. The grips are rated to 35 metric tons for a static tensile load, and 25 metric tons for fatigue loads. Maximum gripping pressure is 3000 psi. The jaw insert faces are hardened tool steel and are serrated for increased gripping effectiveness.

All tensile tests are conducted under manual control and dual ramp input, controlling the crosshead motion. The tests on the glass/epoxy and carbon/epoxy specimens are conducted at a crosshead speed of 0.00143 inches/second. Crosshead speed is increased to 0.00286 inches/second for the Kevlar/epoxy and sandwich composites. The load calibration of all glass/epoxy specimens is 10,000 pounds, corresponding to 10 volts. The calibration is increased to 20,000 pounds per 10 volts for carbon/epoxy and Kevlar/epoxy. The exception to this is that for sandwich materials J and K, where the calibration is set to 50,000 pounds per 10 volts to accommodate the higher loads expected during the tests.

Gripping pressure for all tests with the exception of the sandwich materials is 1000 psi. Sandwich materials J and K are tested at a gripping pressure of 400 psi.

Measurements to determine initial-slope tension modulus are obtained using the MTS Model 632.11B-20 axial extensometer with a gage length of 1 inch and a

maximum strain range of ±15 percent. Extensometer output is fed to an integral X-Y pen and paper plotter. Calibration of the plotter is set to 4,000 micro-strain per 1 volt (0.004 in/in = 1 volt).

Elevated temperature conditioning is conducted in an environmental chamber. The chamber consists of three 1000-watt Lowel DP lights suspended from a supporting framework approximately 10 inches from a refractory material platform. The spots from the lights converge at this platform, where the composite specimens are placed for conditioning one at a time. Temperature is monitored by an Omega 2176A Digital Thermometer and a T-type Copper-Constantan thermocouple with a range of -99.8^{0}F to 752.0^{0}F.

The environmental conditioning process commences with all three lights being placed in the "on" position. When the temperature at the platform reaches 560^{0}F, as determined by the thermocouple reading, the composite specimen is inserted into the chamber and placed on the platform. After one second, the lights are turned off simultaneously. The test material is allowed to cool naturally and is removed from the chamber.

Slow Cook-Off

Slow Cook-off testing is conducted in a Lindberg Model 51442 muffle furnace. The furnace is capable of reaching and maintaining a temperature of 2192^{0}F. The heating elements consist of a composite of helically-coiled iron, chrome and aluminum alloy wire and Moldatherm. (Moldatherm is a Lindberg trade name for ceramic fiber insulation.) Chamber dimensions of the furnace are 7.5 inches x 5.25 inches x 14 inches.

The furnace is controlled by a Lindberg Type 59344 control console. Temperature is monitored by a Type PL2, Platinell II thermocouple. The thermocouple range extends from 32^0F to 2192^0F.

Slow cook-off test specimens are cut from panels into dimensions of approximately three square inches. Actual specimen dimensions range from approximately 1 inch by 3 inches to approximately 1.5 inches by 2 inches. The furnace is pre-heated to the required temperature. The samples are arranged on refractory material, and are inserted into the test chamber. After one hour, the specimens are removed and are qualitatively examined. Charring, discoloration, and any other noticeable changes to the materials are noted and reported.

The slow cook-off test is conducted on various samples at temperatures of 237.50^0F, 356.25^0F and 475.00^0F. These temperatures represent varying levels of thermal environments.

Fast Cook-Off

An oxyacetylene hand-held torch is used to generate the heat source for fast cook-off testing. Testing is conducted in a toxic-gas-approved ventilating hood to prevent noxious fumes from spreading outside the test area. Heat-protective gloves, shaded eye protection, and a set of tongs are required to ensure adequate safety.

Calibration of the surface temperature of the composite during flame impingement is necessary to determine proper temperatures are being attained. To conduct this calibration, a sacrificial piece of material J is used. A 1/32 inch hole is drilled through the specimen, and the beaded end of a K-type Chromel-Alumel thermocouple (accurate to 1999^0F) is inserted into the hole. The thermocouple is inserted until the end is flush with the surface of the composite to be exposed to the

flame. Holding the material with tongs, the flame distance to the specimen is varied until it is possible to achieve a 1000^0F surface temperature on the specimen within the first 30 seconds of exposure to the flame, and a steady-state average temperature of 1500^0F.

Once calibration is complete, each specimen is conditioned individually in the flame. The exposure lasts for 15 minutes or until the specimen has lost all structural integrity, whichever occurs first. Loss of structural integrity is apparent when the epoxy has been burned away, leaving nothing but exposed fibers in the path of the flame, or when the sample burns away under flame impingement and cannot support its own weight. Qualitative observations are made during testing at one minute intervals.

APPENDIX C: DATA

This appendix contains the experimental results for width effects determination and tensile testing.

Width Effects Determination

TABLE C1 Ultimate Tensile Strength Data of Material C for Width Effects Determination Testing.

Specimen Width (in)	Cross-Sectional Area (in^2)	Tensile Strength (psi)
1	0.026	7,692
1	0.026	14,615
1	0.026	10,769
1.25	0.031	12,800
1.25	0.033	13,846
1.25	0.033	13,538
2	0.052	15,385
2	0.056	13,571
2	0.052	14,423
3	0.081	14,074
3	0.084	13,452
3	0.081	13,951

Tensile Tests

TABLE C2 Ultimate Tensile Strength and Tensile Modulus Data for Materials A Through K Tested at Room Temperature and Humidity.

Specimen	Cross-Sectional Area (in^2)	Tensile Strength (psi)	Tensile Modulus (psi)	Notes
R-A1[a]	0.068	-	772060	b
R-A2	0.059	15593	815680	
R-A3	0.056	14286	736610	c
R-A4	0.056	17143	-	
Avg.	0.060	15674	774780	
R-B1	0.076	26710	877200	b
R-B2	0.091	24725	792500	
R-B3	0.077	29351	930736	c
R-B4	0.076	32368	930736	
Avg.	0.080	28289	882793	
R-C1	0.066	10910	587121	
R-C2	0.055	15636	636364	d
R-C3	0.059	12542	550847	
Avg.	0.060	13029	591444	e
R-D1	0.084	14881	-	
R-D2	0.085	14921	793651	
R-D3	0.073	12192	879000	
Avg.	0.081	13998	836325	
R-E1	0.066	6364	340909	
R-E2	0.069	6377	353261	d
R-E3	0.069	6087	353261	
R-E4	0.066	6667	-	
Avg.	0.068	6374	349144	

(Continued on next page)

- Indicates data not obtained.

a The "R" in each specimen designation indicates "Room Temperature," and the letter after the hyphen represents material designation.

b Specimens numbered 1 and 2 came from the same panel.

c Specimens numbered 3 and 4 came from the same panel

d Failed near the tab.

e All specimens of this designation were noticeably resin-rich.

TABLE C2 (Continued) Ultimate Tensile Strength and Tensile Modulus Data for Materials A Through K Tested at Room Temperature and Humidity.

Specimen	Cross-Sectional Area (in^2)	Tensile Strength (psi)	Tensile Modulus (psi)	Notes
R-F1	0.089	9775	618000	
R-F2	0.077	13247	600650	
R-F3	0.077	11429	682000	
R-F4	0.079	12025	-	d
R-F5	0.077	12208	-	
Avg.	0.080	11737	633550	
R-G1	0.119	14790	609244	
R-G2	0.114	13333	625000	
R-G3	0.120	14000	677083	
Avg.	0.118	14041	637109	
R-H1	0.137	30511	1.124 E6	
R-H2	0.149	24899	0.982 E6	
R-H3	0.149	29866	-	
Avg.	0.145	28425	1.053 E6	
R-I1	0.051	220000	8.80 E6	
R-I2	0.0575	209222	8.70 E6	
R-I3	0.052	216923	8.66 E6	
Avg.	0.0535	215382	8.72 E6	
R-J1	0.303	57360	-	
R-J2	0.310	52742	2.2 E6	d
R-J3	0.296	56081	2.4 E6	d
Avg.	0.303	55394	2.3 E6	
R-K1	0.410	-	1.8 E6	
R-K2	0.419	-	1.9 E6	
R-K3	0.390	-	1.8 E6	
Avg.	0.406	-	1.8 E6	

- Indicates data not obtained.

d Failed near the tab.

TABLE C3 Ultimate Tensile Strength and Tensile Modulus Data for Materials A Through K Exposed to a 560^{0}F Environment for One Second and Tested at Room Temperature and Humidity.

Specimen	Cross-Sectional Area (in^2)	Tensile Strength (psi)	Tensile Modulus (psi)	Notes
E-A1	0.055	18182	840910	b
E-A2	0.057	19649	789470	
E-A3	0.059	16610	881360	c
E-A4	0.054	17778	-	
Avg.	0.056	18055	837250	
E-B1	0.081	25556	791390	b
E-B2	0.087	25172	718390	
E-B3	0.076	26973	940000	c
E-B4	0.088	26023	738640	d
Avg.	0.083	25931	803588	
E-C1	0.073	10137	438360	
E-C2	0.061	12459	522540	
E-C3	0.055	12364	606060	
Avg.	0.063	11653	522320	e
E-D1	0.074	17432	710230	
E-D2	0.071	11972	862680	
E-D3	0.076	15132	723680	
Avg.	0.074	14845	765530	
E-E1	0.065	7077	326920	
E-E2	0.078	5641	256410	d
E-E3	0.074	5946	270270	d
E-E4	0.060	7667	-	d
E-E5	0.057	6316	-	
Avg.	0.067	6529	284530	

(Continued on next page)

- Indicates data not obtained.

a The "E" in each specimen designation indicates "Elevated Temperature," and the letter after the hyphen represents material designation.

b Specimens numbered 1 and 2 came from the same panel.

c Specimens numbered 3 and 4 came from the same panel

d Failed near the tab.

e All specimens of this designation were noticeably resin-rich.

TABLE C3 (Continued) Ultimate Tensile Strength and Tensile Modulus Data for Materials A Through K Exposed to a 560°F Environment for One Second and Tested at Room Temperature and Humidity.

Specimen	Cross-Sectional Area (in^2)	Tensile Strength (psi)	Tensile Modulus (psi)	Notes
E-F1	0.080	12375	723680	
E-F2	0.079	10127	723680	
E-F3	0.085	10588	-	
E-F4	0.082	13902	-	
E-F5	0.079	-	-	
Avg.	0.082	11748	723680	
E-G1	0.114	14386	581140	
E-G2	0.114	13793	625000	
E-G3	0.116	15690	581900	
Avg.	0.115	14623	596010	
E-H1	0.138	32174	1.087 E6	
E-H2	0.144	29375	1.042 E6	
E-H3	0.140	30571	1.071 E6	
Avg.	0.141	30707	1.067 E6	
E-I1	0.061	217049	8.40 E6	
E-I2	0.060	219667	8.60 E6	
E-I3	0.059	211525	9.10 E6	
Avg.	0.060	216080	8.70 E6	
E-J1	0.307	52932	2.24 E6	
E-J2	0.314	52866	2.24 E6	
E-J3	0.282	54225	2.44 E6	d
Avg.	0.301	53341	2.31 E6	
E-K1	0.410	-	1.71 E6	
E-K2	0.419	-	1.66 E6	
E-K3	0.390	-	1.68 E6	
Avg.	0.406	-	1.68 E6	

- Indicates data not obtained.

d Failed near the tab.